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Factors affecting heat flow through roof sections covered with sheet steel

Norton C. Ives
Iowa State College

FACTORS AFFECTING HEAT FLOW THROUGH

ROOF SECTIONS COVERED WITH SHEET STEEL

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Norton C. Ives

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Approved:

Henry Giese
In charge of Major work

J. Brownlee Davidson
Head of Major Department

R. E. Buchanan
Dean of Graduate College

Iowa State College

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INTRODUCTION

Justification for the Study

The importance of an adequate roof on farm buildings, which would more completely fulfill the essential requirements for an ideal roofing material, led the Republic Steel Corporation to cooperate with the Iowa Agricultural Experiment Station to set up a research project for the purpose of studying the characteristics, from the standpoint of heat insulation, of galvanized sheet steel as a roofing material.

Man has striven for years to produce a roofing material incorporating the following features as they have been laid down from years of experience:

1. Resistance to fire
2. Structural stability
3. Resistance to the elements of nature, which would provide a long life and a low upkeep cost
4. Resistance to flow of heat
5. Resistance to the penetration of water and in many cases water vapor
6. Low-cost
7. Ease of application
8. Pleasing appearance to the eye

In an article appearing in the Agricultural Engineering Journal, A. J. Deniston, Jr. (6) writes:

"To the unprejudiced mind, one of the best roofing materials which has been developed for use on farm buildings, every phase of the matter being considered, is galvanized sheet steel roofing."

In another article M. C. Betts (5) writes, "Galvanized steel is comparatively cheap and easily applied... It has one pronounced virtue, from a roofing standpoint, in that it affords excellent protection from fire due to sparks or brands." He also adds, "It has no insulation value.", and in conclusion, "..., I think I have made clear that farm roofing presents some nice problems for research investigation."

As a result of a survey of "The Uses of Steel in Iowa Farm Buildings," which was made by W. D. Scoates, the first research fellow to conduct work on this project, the problem which seemed most pertinent for immediate study was one designed to solve the present principal objection in the use of sheet steel roofing on farm buildings, namely, that "It is hot in the summer and cold in the winter."

Therefore, to improve galvanized sheet steel as a roofing material the one principal requirement which is yet to be adequately satisfied is that of providing resistance to the flow of heat through roof sections covered with galvanized sheet steel roofing.

Objectives of the Study

The purpose of this study is to analyze how different roof sections covered with galvanized sheet steel roofing retard the flow of heat through them due to a difference between the outside surface temperature of the roof and the inside temperature of the air under the roof and to compare the over-all insulation abilities of different roof sections to the flow of heat from solar radiation and/or from a temperature difference between the inside and outside air. The following specific objectives have presented themselves to be solved in order to supply the essential information needed for an analysis of the problem: (1) To find the factors which affect the amount of heat entering a given roof section when exposed to solar and sky radiation, an air temperature difference, or both of these conditions acting simultaneously; (2) to analyze these factors as to their nature and importance in affecting heat flow through a roof structure, and (3) to study and compare the relative abilities of different roof sections covered with galvanized sheet steel roofing with regards to their insulation properties to stop heat flow from solar radiation and/or an air temperature difference.

HISTORICAL

The Project

This study is a part of the general project set up at the Iowa Agricultural Experiment Station entitled, "The Utilization of Steel in Farm Structures." Work to the present time has followed one principal field of endeavor, that of analyzing the abilities of different roof sections covered with sheet steel roofing with regard to their efficiencies as insulators to the flow of heat from solar radiation.

Part of this study is essentially a continuation of the problem set up by the first Research Fellow, William D. Scoates, and should the reader desire to secure more detailed information concerning the construction of the original testing apparatus, it is advised that he refer to Scoates' thesis, "The Effect of Sheet Steel Roofing on Interior Temperatures." (25)

To further analyze the abilities of roof sections covered with galvanized sheet steel roofing, two extra roof sections have been added to the original test house incorporating an added feature, that of ventilation within the roof section. Also, instruments to measure the amount of solar and sky radiation falling upon a horizontal surface and to determine more accurately the wind velocity over the roof surfaces have been introduced into the study. For winter readings heating units have been added to the several compartments to provide a more complete study as to their insulating properties for winter conditions.

Review of Literature

That solar radiation is a potent factor affecting heat flow through roofs was clearly shown by Houghten and Gutberlet (14), who found by actual measurement that a black oilcloth surface maintained perpendicular to the sun's rays on a clear day absorbed a maximum of 273 B.T.U./hr./sq. ft. They also found that lamp black, red brick, and aluminum bronze painted surfaces likewise held perpendicular to the sun's rays showed 94.0, 63.4 and 28.2 percent as high a rate of absorption as did the black oilcloth under similar conditions.

Considerable work has been done by various investigators to find the abilities of different roof treatments in stopping heat flow from solar radiation. Kern (15) approached the problem by classifying the various ways to reduce solar heat loads into four basic methods: (1) cutting off the sun rays, (2) increasing the amount reflected, (3) increasing the resistance of the roof, (4) use of water cooling.

In the case of the first method it would be necessary to place a protection over the surface exposed and maintain adequate ventilation underneath. Kern states, "It should be noted that the same effect can be secured from a well ventilated air space between the roof and ceiling, as for example, an attic." He continues, "The second method which attempts to increase the amount of solar radiation reflected by the surface, involves changing the character of surface. It should be remembered that the ideal treatment would give the roof a pure white and highly polished surface. The closer the treatment approaches this ideal the lower the solar heat load." Relative to this he explained, "One of the simplest and most effective paints for a bituminous roof is a white-wash made with tallow." To prepare this "Quicklime is slaked in a bucket and during slaking, tallow is added in the proportion of 5 pounds to 70 pounds of lime. This mixture is then thinned to the consistency necessary for brushing. Two coats will cover most surfaces... This paint resulted in roof temperatures actually lower than the maximum air temperature, wore fairly well and was quite waterproof." Concerning the third method, "This method has the advantage of not only reducing the heat load in summer but also reducing the heat loss during the winter. It has been pointed out that the presence of insulation in the roof is likely to result in a higher outer surface temperature and consequently increase the amount of heat transmitted over what may normally be expected. Actual tests have shown that

1/2-inch wallboard underneath the waterproofing resulted in temperature reductions of 23 1/2°F.; 1-inch cork resulted in 31 1/2° F. reduction; 2-inch cork, 35 1/2° F., as against a 35° F. reduction with a whitewash finish alone." Relative to the last method, "...where water is kept on the roof in the form of a pool, use is made of the reflective ability, evaporation, and heat storage ability of the water to reduce the sun load. When this method is used, the roof temperature approaches the outside air temperature and it is the practice of some engineers to assume the roof temperature equal to the maximum outside air in calculating the heat gain of the building. It should be remembered... the outside air surface resistance has been eliminated." Concerning depth of water, "...it is possible that 1/2-inch of water on a slag roof will have more cooling effect than 2 inches of water. ...the area" - of the roofing slag - "above the water level would present a larger surface to the wind and more water probably would be evaporated. If water is sprayed onto the roof and the rate of spraying is controlled so that most of the water evaporates as it touches the roof, the roof surface temperature will approach the wet bulb temperature of the air."

Williams (31) found that, "Temperatures of exposed surfaces of contents of uninsulated corrugated iron sheathed buildings can be lowered at least 20° F. by lining with 7/16-inch masonite, celotex, etc."

Molenaar and Perry (19) make the following comments concerning roofs exposed to solar radiation: "Wood shingles on solid sheathing gave the best performance of any of the uninsulated roofs. Although galvanized iron on strips made a very hot roof, galvanized iron on sheathing was only about 25 percent hotter than wood shingles on sheathing, and was considerably cooler than roll roofing or composition shingles. ... The effect of the bright aluminum paint was quite marked, making the galvanized iron on strips as cool as unpainted galvanized iron on sheathing, and making that on sheathing as good as aluminum painted wood shingles."

For the purpose of making a thermal analysis, Rowley (21) has divided a wall into sections of homogenous material, air spaces and surfaces. He measured the following reductions in surface conductance coefficients caused by covering an ordinary surface with bright aluminum foil:

Temperature Degrees Fahrenheit	Reduction in Coefficient
20	0.559
40	0.634
60	0.711
80	0.797
100	0.887
120	0.99

Queer (20) found that it would take 1.06 inches of board or blanket fill insulation to produce the same insulating effect as one sheet of bright metal foil and applied so that each had the same air space advantage. He also found that the total conductance of a 3 5/8-inch air space when bounded by ordinary surfaces was 1.1 B.T.U./sq. ft./hr. °F.

In a Bureau of Standards circular (28) the following statement is made: "Investigation has shown that the differences in the respective thermal conductivities of the various light fibrous or cellular materials are not very great. The conductivities of most materials manufactured and sold primarily as insulators fall within the range 0.25 to 0.35 B.T.U./hr./sq. ft./°F./inch."

Spriggs (27) reports an average conductance of cornstalk insulation, one type used in this study, as 0.26.

Concerning the effects of air velocities on surface coefficients Rowley and others (22) found that the air temperatures 0.5-inch out from the surface were substantially constant, and in their study they used 1.0 inch as the normal distance from the surface to measure the air temperature for the calculations of surface coefficients. They also found, "For air velocities ranging from 0 to 35 mph, the coefficients have followed a straight line relation." They placed the zero air velocity constant at 1.34 and the 35 mph constant at 0.4. In another report (23) they state, "Whether or not humidity affects surface conductance is a point to be considered. If it does, the effect is of small consequence, because, although there was no provision made for keeping constant humidities in these tests, there was no appreciable variance in the results. The effect of a wet surface on the surface coefficients is also a question for further consideration."

ANALYSIS OF PROBLEM

This part of the work was primarily devoted to the study of heat flow in its special application to this problem and the factors which affect its magnitude, the purpose being to formulate the proper procedure by which this study could be done most effectively.

Factors Affecting Heat Flow Through a Structure

For any building exposed to natural weather conditions, heat flow from the outside to the inside or vice versa is accomplished with the heat being manifested in one or a combination of the following forms: (1) ventilation heat, (2) filtration heat, (3) sun heat, (4) heat produced or absorbed within the structure by body heat; electrical, mechanical, or heat energy; and humidity changes; and (5) transmitted heat.

<u>Ventilation heat</u> is the heat carried into or out of a building by the ventilation air. <u>Filtration heat</u> is the heat carried into or out of a building by all other air changes not included as ventilation air, such as the air coming

through porous walls, around doors and windows, etc. Sun heat, as considered here, manifests itself only when the sun's rays can enter a building in the form of radiant energy, as may be the case for glass windows in a building. The radiant energy is converted into heat upon striking opaque objects within the building. Heat produced or absorbed within a building varies in magnitude depending upon its use. For livestock structures the animals themselves usually furnish this heat. Humidity changes, while actually giving or taking heat from the air, are usually negligible. For a house or industrial building the heat produced may be from a number of energy sources, and for the purpose of designing heating or cooling loads the principal ones are taken into consideration. Transmitted heat is heat flow due to a temperature difference between two points in a material. It is usually considered in connection with buildings as the heat flow through the floors, walls, ceilings, and roofs due to a temperature difference between the inside and outside surfaces.

For any opaque substance that is impervious to the flow of air and moisture the only possible means of heat flow is manifested in the form of transmitted heat. Since this study is concerned with roof sections that were designed for a minimum of air and moisture penetration the other four means of heat flow are not regarded except as they manifest themselves as a result of the conditions of nature.

An enumeration of the various factors affecting the transmitted heat flow through a roof section has been made by various investigators. Houghten and Gutberlet (14) have listed the factors which affect the heat absorption and transmission of a wall or roof section when exposed to direct sunlight. These factors are shown on the diagram in Fig. 1 which represents a roof or wall section exposed to direct radiation from the sun.

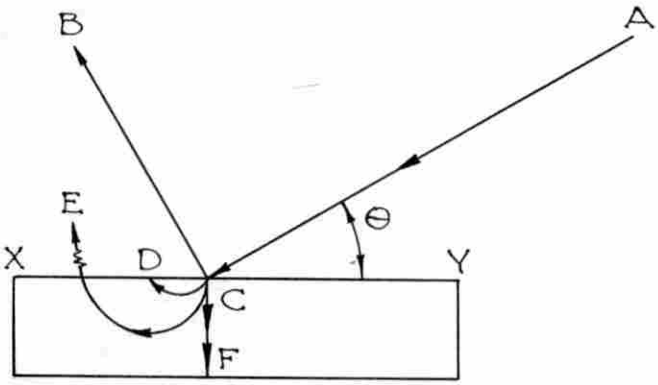


Fig. 1. Factors affecting heat flow through a structure

(A) represents the total radiant energy impinging upon the surface. On a day when the sun is shining the total radiant energy consists of three factors: (1) the radiation directly from the sun's rays, (2) the radiation from a clear or partly clouded sky, and (3) the radiation from the surrounding trees and buildings. When the sky is completely overcast with clouds, the total amount of impinging radiation is limited to the last two factors, and for a roof located apart from other buildings and trees, the third factor is negligible.

The amount of radiation falling on a roof or wall surface per unit area depends upon the angle of incidence, or the complement of the angle θ.

Of this total portion (B) does not enter at all, but is reflected back to the sky. The amount reflected depends upon the character of the roof surface, the kind of radiation impinging upon it, and upon the angle θ.

Let (C) represent the part that is not reflected. Immediately upon entering the surface this radiant energy is completely transformed into heat which raises the temperature of the roof surface. Due to this rise of temperature the roof surface may be considered as an independent radiator, and it re-radiates heat waves back to the sky. The rate of this radiation depends upon the surface characteristics of the roof and is proportional to the difference of the 4th power of the absolute temperatures between the roof surface and the particles absorbing this radiation. This is represented by D.

Another portion (E) of the total amount entering the roof surface is lost back to the air by convection currents of the air. The magnitude of this factor depends upon the absolute temperature of the roof surface and the temperature difference between the air and roof XY. It also depends upon the velocity of air passing over the roof and the nature of its surface.

The remaining portion (F) starts its progress through the roof or wall section raising the temperature of each part as it travels until it is taken from the opposite surface by convection and radiation or is left within the roof as stored heat. The amount passing through depends upon the over-all insulating properties of the structure, the heat capacity for storage and the temperature difference between the roof surface XY and the inside air.

To measure individually each of these factors as to their effect on heat flow through a roof section would indeed become quite unfeasible in this type of study. However, it is convenient to divide them into two broad classifications for study:

1. The environmental factors
2. The physical properties of the roof structure

Environmental factors

There are three measurements that if made both quantitatively and qualitatively will include all the environmental factors affecting heat flow through a roof section, namely: (1) impinging radiation, (2) outside air temperature, (3) and wind velocity over the surface. There are other environmental factors, such as relative humidity and wind direction which would appear to be influential. However, work by other investigators showed no consideration given to the effect of relative humidity on heat flow through a structure, and a study concerning the effect of wind direction (24) indicated that, "For all practical purposes, it would appear that the surface coefficients as obtained for air flow parallel to the surface might well be used without any correction for the angle of the wind. Tests were made for only one mean temperature, but there is no reason to believe that similar relations would not hold for other mean temperatures."

While man can do nothing to change these factors even though their nature and magnitude of effect on heat flow are determined, yet they must be determined in an analytical study, since to properly design a structure against heat flow the conditions to which it is subjected should be shown.

Physical properties of the roof structure

Herein must lie the solution by which the desirable conditions relative to heat flow through a structure may be obtained. However, in this analysis it may be assumed that once a certain type of structure is determined its physical properties remain constant. Therefore, it appears logical to study the physical factors of a roof section which affect heat flow, and then incorporate the features which appear from a theoretical study to be most effective in retarding this heat flow.

The characteristics of a roof structure which have a marked effect on heat flow through it may be classified broadly into: (1) the character and nature of the roof surfaces; (2) the over-all insulation ability of the roof structure, which would include insulation against heat flow by one or a combination of three methods - radiation, conduction, and convection; (3) the heat capacity of the roof structure.

All heat flow takes place by convection, conduction, and/or radiation. The following definitions are taken from Maxwell's Theory of Heat (4): "Convection is the motion of the hot body itself carrying its heat with it." It is seen that for this process the substance must either be a liquid or a gas. "Conduction is the flow of heat through an unequally heated body from places of higher to places of lower temperature." Conduction may take place in solids as well as in liquids and gases. "In radiation, the hotter body loses heat, and the colder body receives heat by means of a process occurring in some intervening medium which does not itself thereby become hot." This definition is so stated that it does not commit itself to the theory of radiation being transmitted by ether waves, which is still an unsettled theory in modern science.

Extensive studies and investigations have been carried on to determine the abilities of various building materials to retard heat flow by the three methods listed above. As a result of this work the nature of heat flow has been quite well established by the various authorities.

The most popular method used to determine the flow of heat at the present time through wall or roof structures makes use of the following well known equation,

$$H = UA(t_i - t_o) \qquad \text{Eq. 1}$$

where H = the heat transmitted, B.T.U./hr.

U = the over-all coefficient of heat transmission B.T.U./hr./sq. ft./°F.

A = the area of wall, etc. sq. ft.

t_i = inside air temp. °F.

t_o = outside air temp. °F.

The factor U is an over-all measure of several constituent factors. For a homogeneous material with air on both sides the over-all heat transmission coefficient may be computed (26) from the following equation,

$$U = \frac{1}{\frac{1}{f_i} + \frac{1}{f_o} + \frac{x}{k}} \qquad \text{Eq. 2}$$

where f_i and f_o are called the surface conductance coefficients, expressed in B.T.U./hr./sq. ft./°F.

x = the thickness of the homogeneous material, inches

k = the coefficient of heat conductivity of this material B.T.U./hr./sq. ft./°F./inch thickness

For homogeneous material or for built-up wall sections this equation becomes more involved but the principle is essentially the same. For future use the following symbols are defined here.

C = the conductivity coefficient, B.T.U./hr./sq.ft./°F. for the standard thickness of the material or the thickness given

T = the absolute temperature, °F.

The values of the surface conductances, f_i and f_o are affected by the character of surface, the air velocity over the surface and, as will be shown later, the mean temperature of the surface and adjacent air. When the above two equations are used to compute the heat transfer through a structure, the value of f_i and f_o include heat losses due to radiation, conduction, and convection. Also, if the wall is not of a homogeneous material, it is more than likely that all three methods are manifested within the wall section before the heat appears at the opposite surface. Therefore, to analyze structures for their resistances to heat flow, a thorough understanding of the three fundamental methods of heat transfer is essential.

Radiation is a term usually applied to all electromagnetic waves. In heat transfer problems it deals with the electromagnetic waves set up by temperature, and is more specifically thermal radiation. Thermal radiation is emitted by all matter, depending only upon the nature and temperature of the matter. It is a well established fact that the rate of radiant energy transfer between two bodies can be expressed by the following equation,

$$H = S(T_1^4 - T_2^4) \qquad \text{Eq.3}$$

where H is the heat emitted from unit area per unit time

S is a constant depending on the emissivity of the surface

T_1 and T_2 are the absolute temperatures of the surfaces emitting and receiving radiation respectively

To develop the various parts of this equation consider a theoretical gray surface surrounded completely by theoretical black bodies. A gray surface is defined for convenience as a surface whose emissivity is the same at all wave lengths and temperatures. A theoretical black body is considered to be a completely absorbing body of all range wave lengths with a non-reflecting surface, and from Kirchoff's law, which states that for any given temperature and wave length the ratio of the coefficient of emission to the coefficient of absorption is the same for all substances, it is seen that a black body may be termed a "full radiator." Consequently its emissivity is taken as a standard with which the emissivity of other non-black bodies are compared. This comparison is expressed by a constant E, called the emissivity of a surface and being defined as the ratio of the intensity of the radiation of any given wave length emitted from unit area of a surface to the intensity in the same wave length from unit area of a black body at the same temperature (7. p 10). It should be noted that this constant for any surface is always less than one, since no body can emit more strongly than a black body at the same temperature and in the same wave length. For this special case the above equation becomes

$$H = 17.3 \times 10^{-10} E_1(T_1^4 - T_2^4) \text{B.T.U./hr./sq. ft.} \qquad \text{Eq. 4}$$

The factor 17.3×10^{-10} is an experimentally determined constant, called Stefan's constant, which expresses the total amount of radiation that is emitted from a black body, B.T.U./hr./sq. ft./(°F. abs.)^4. Stefan's law states that for an independent radiator $H = KT^4$, and 17.3×10^{-10} has been agreed upon as the value of K (7. p. 12). The term $17.3 \times 10^{-10}E_1T_1^4$ represents the amount of heat being given off by the gray surface due to its absolute temperature. The second term $17.3 \times 10^{-10}E_2T_2^4$ represents the total emission of the black bodies to the gray surface due to their absolute temperature. The gray surface absorbs only part of this emitted radiation, E_1, returning the remainder to be absorbed by the black bodies.

It can be proved (7. p. 28) for two, equal in size, parallel surfaces separated by a distance small in comparison with their dimensions and having any surface characteristics, that the heat lost by radiation from one to the other may be expressed by the following equation,

$$H = 17.3 \times 10^{-10} \frac{E_1E_2}{E_1E_2E_1E_3} (T_1^4 - T_2^4) \text{B.T.U./hr./sq. ft.} \qquad \text{Eq. 5} \quad ?$$

where E_1 and E_2 are the emissivity coefficients of the two surfaces and T_1 and T_2 are their absolute temperatures.

It should be emphasized that the coefficient of absorption, which according to Kirchoff's law is directly proportional to the coefficient of emission for the same conditions, depends upon the nature of the material, while the absorptive power of a body can be modified by surface treatment. For instance, steel, which has a high absorptive power of radiant heat, with a highly polished surface would absorb less heat than if it had an oxidized surface, since the highly polished surface excludes the entrance of much of the heat to be absorbed.

When radiation falls upon an opaque body

$$R + A = 1 \qquad \text{Eq. 6}$$

where R = the reflecting power

A = the absorptive power

The absorptive power is then dependent solely upon the surface characteristics of the body and may be changed by surface treatment. Since ordinary solids are opaque to a wide range of radiation, their emissivities depend entirely upon their surface reflecting characteristics. As a result, it can be shown (8. p. 10) that for all substances

$$E = A$$

Or, in words, the emissivity of an opaque substance is equal to the absorptive power of the substance. Substituting E for A in the above equation,

$$R + E = 1 \text{ or } R = 1-E$$

Therefore, if the emissivity of polished aluminum is 0.02, the reflecting power = 0.98.

As previously stated, for a given wave length the emissivities of different materials depend only upon their nature and temperature. The emissivities in Table I of various substances have been listed (7. p. 17-22) for the wave lengths given.

For temperatures below 212°F. it has been found (12) that various colored paints were indistinguishable as regards heat radiation. It should also be noted that the effect of inserting an opaque material of negligible thickness in the center of an air space of a wall section is a reduction of the heat flow by one-half. Let it be assumed that the temperature of the partition be the mean temperature of the hot and cold surfaces. With this the condition it is readily seen from equation 5 that for small temperature differences approximately one-half of the original amount will travel from the hot surface to the partition, and, likewise, one-half will travel from the partition to the cold surface. The effect of an opaque partition of negligible thickness is then to reduce the heat flow by radiation to approximately one-half its original value. Two partitions would reduce it to one-third its original value, etc. It is obvious by this reasoning that the effect of minute particles as found in many types of "loose-fill" insulation would be to reduce the heat transfer by radiation

Table I. Emissivities of Various Substances

Substance	Wave Length			
	1.8 u 2,500°F.		0.95 u 5,000° F.	
Roofing Materials				
Galvanized iron, whitewashed	37		22	
Aluminized felt	33		29	
Enameled steel, white	65		45	
Galvanized iron, new	42		67	
Bituminous felt	90		88	
Galvanized iron, very dirty	90		89	
	24 u	8.8 u 125°F.	4.4 u 750° F.	0.95 u 5,000° F.
Pigments				
Lampblack paint	96	96	97	97
Platinum black	92	91	95	97
Blue (Co_2O_3)	94	87	86	97
Red (Fe_2O_3)	91	96	70	59
Green (Cu_2O_3)	91	96	70	55
White (Al_2O_3)	94	98	79	12
White (ZnO	95	97	91	14
	9.3 u 100° F.	5.4 u 500°F.	3.6 u 1,000° F.	0.95 u 5,000°F.
Metals				
Aluminum, polished	4	5	8	26
Aluminum, rough	7	-	-	-
Aluminum, oxidized	11	12	18	-
Copper, polished	4	5	18	26
Copper, rough	74	-	-	-
Copper, oxidized	-	-	57-73	-
Steel, polished	7	10	14	37
Steel, oxidized	79	79	79	-
Zinc, pure polished	2	3	4	50
Zinc, on sheet iron	23	-	-	-
Miscellaneous Materials				
Surface soil	38			
Plaster of paris	79			
White paper	80			
Polished glass	90			
Glass	90			
Planed oak	91			

through these materials to a point where it may be neglected.

One marked distinction between radiation and conduction is that radiation can take place through a vacuum, but conduction can only take place through a continuous matter. The present theory of conduction heat transfer (7. p. 58) is explained by the kinetic energy difference that molecules in one layer of a substance possess over those in an adjacent layer when the first layer is at a higher temperature. As a result there is a tendency for the molecules with greater energy to transfer some of their energy by mechanical action or even by the emission and absorption of radiation to those having less energy. In this way the energy, or heat, tends to become equally distributed as manifested by the approach of equal temperatures, or if temperature differences are maintained, there is a heat flow from the hotter to the cooler layers.

The quantity of heat flowing by conduction through a substance is directly proportional to the temperature gradient, dt/dn in the direction normal to its surface, and may be expressed by

$$H = -U\, dt/dn \qquad \text{Eq. 7}$$

where U is the proportionality constant. If the temperature gradient rise and the direction of heat flow are considered positive, the minus sign is necessary, since heat flows down the temperature gradient.

If the C. G. S. system is used, the expression of U becomes the quantity of heat in gram calories which flows in one second through a one-centimeter cube where there is a difference of temperature of one degree centigrade between the opposite faces, the condition so existing that there is no gain or loss of heat through the edges of the cube. In the British system U is defined as the quantity of heat in B.T.U. which flows per square foot per hour through one inch thickness of material for a difference of temperature of one degree Fahrenheit between the faces (11. p. 9). U in the British system of units is 2,903 times greater than U expressed in the C. G. S. system.

It is usual to classify heat losses by convection into two groups: (1) natural and (2) forced convection. In natural convection the air is considered to be still except for gravity currents set up by density changes in the air produced by heat flowing from the surface to the air or vice versa. In forced convection the ambient air is considered to be in motion due to some external force and while the gravity currents exist, they usually are relatively small and may be considered negligible.

The flow of heat by convection is complicated in either case, not only because of the turbulent motion of the air but because of the many influential factors such as the velocity, density, specific heat, conductivity, and viscosity of the fluid, as well as the size, shape and temperature of the body losing or gaining heat. Because there are so many variable factors, a theoretical analysis of this type of heat flow has proven to be extremely complicated.

Experimental work over a wide range of conditions has shown that the flow of heat by convection is proportional to the 5/4 power of the temperature difference between the surface and the ambient fluid (7. p. 96). Griffith and Davis (12) derived the following empirical formula for convection heat flow from a vertical plane surface:

$$H_c = A\ \theta^{1.25} \qquad \text{Eq. 8}$$

where H_c = the heat flow by convection, B.T.U./hr./sq.ft.

" $\log (A - 0.32) = -1.5L$

" L is measured in feet height of vertical plane

" θ = the temperature excess, or the difference between the surface temperature and the air temperature

The disturbance of the atmosphere due to natural convection currents has been found (12) to be confined within a distance of two centimeters from the surface. The same investigators found that the heat loss from a vertical plane surface could be expressed by the following equation:

$$H_c = 0.30 \times \theta^{1.25} \qquad \text{Eq. 9}$$

For this particular condition at a mean air temperature of 40°C. the value of A in equation 8 = 0.30. Concerning the position of the wall it has been shown (30) that nearly three times more heat is lost for a horizontal position with the heat flow upward than with the heat flow downward. For vertical positions the loss is not the average but is nearer the greater of the two. The effect of height and width of air space within a wall upon the flow of heat by convection has no effect for heights greater than 24 inches and widths greater than 1/2 inch (12, 30).

Emphasis should be given to the fact that 65 to 80 percent of all heat flow takes place by radiation across a vertical air space between ordinary walls (12, 30). To compare the radiation effect across air spaces bounded by various surfaces Table II is given (30). These figures were obtained for surface temperatures for 40° and 60°F. and the effective emissivities of the two sets of surfaces were 0.83 and 0.05, or the average values for ordinary surfaces of wood, plaster, paper, etc. and for polished aluminum, respectively. The effective emissivity for a set of surfaces is equal to $\frac{E_1E_2}{E_1 + E_1 - E_1E_2}$, E_1 and E_2 being the emissivities of the two surfaces, respectively.

Table II. Relative Amount of Radiation and Convection in Various Positions

Position	Eff. E equals 0.05		Eff. E equals 0.83	
	% Convection	% Radiation	% Convection	% Radiation
Horizontal heat down	88	12	31	69
45% heat down	90	10	38	62
Vertical	93	7	43	57
45% heat upward	94	6	48	52
Horizontal heat upward	95	5	55	45

Methods to Measure These Factors

For summer weather conditions

Calculation of solar heat gains. At the present time one of two methods is generally used to compute the heat flow into a structure due to solar radiation. The first (3) makes use of the following equation:

$$Hs = A\ I\ b\ g \qquad \text{Eq. 10}$$

where Hs = the sun heat, B.T.U./hr.

As = the intensity of solar radiation, B.T.U./hr./sq. ft.

b = decimal part of I absorbed

g = decimal part of b transmitted to the inside

It is apparent that to use this formula with accuracy would require careful determination of I, b, and g, which factors vary greatly for the various conditions encountered in a practical application. However, as may be the case in computing the maximum cooling load for a building, if just the extreme set of conditions is desired, these factors have been determined by various investigators and may be used with a fair degree of accuracy.

To use this equation Tables III and IV are given (15) from which the values of b and g may be taken. They were taken from studies of the Building Research Board of Great Britain.

Table III. Decimal Part of Solar Radiation
Absorbed by Various Roofing Materials

Roofing Material	b
Asbestos-cement, white	0.42
Asbestos-cement, 6 mo. exposed	0.61
Asbestos-cement, 12 mo. exposed	0.71
Asbestos-cement, 6 years, very dirty	0.83
Asbestos-cement, red	0.69
Asphalt, new	0.91
Asphalt, weathered	0.82
Bitumen-covered roofing sheet, brown	0.87
Bitumen-covered roofing sheet, green	0.86
Bituminous felt	0.88
Bituminous felt with aluminum surface	0.40
Slate, silver gray	0.79
Slate, blue gray	0.87
Slate, greenish gray, rough	0.88
Slate, dark gray, smooth	0.89
Slate, dark gray, rough	0.90
Tile, clay, machine made, red	0.64
Tile, clay, machine made, dark purple	0.81
Tile, clay, hand made, red	0.60
Tile, clay, hand made, reddish brown	0.69
Tile, concrete, uncolored	0.65
Tile, concrete, brown	0.85
Tile, concrete, black	0.91
Metals:	
Steel, vitreous enameled, white	0.45
Steel, vitreous enameled, green	0.76
Steel, vitreous enameled, dark red	0.81
Steel, vitreous enameled, blue	0.80
Galvanized iron, new	0.64
Galvanized iron, very dirty	0.92
Galvanized iron, white washed	0.22
Copper, polished	0.18
Copper, tarnished	0.64

Table IV. Amount of Absorbed Solar Heat
Transmitted Through Roofs

Roof Conductivity B.T.U./hr./sq. ft./°F.	Decimal Part of Absorbed Radiation Transmitted to Inside
0.10	0.02
0.15	0.03
0.20	0.04
0.25	0.05
0.30	0.062
0.35	0.075
0.40	0.085
0.45	0.095
0.50	0.105
0.60	0.13
0.70	0.15

As for I, the intensity of the solar radiation impinging upon the surface, computations have been based upon measurements made at different laboratories of the maximum solar heat reaching a unit surface for a clear sky. These values have been given (9) for a surface normal to the sun's rays for the different hours of the day, and are shown in Table V.

Table V. Solar Heat Falling on a
Surface Normal to the Sun

Time A.M.	B.T.U./hr./sq. ft.	Time P.M.
6	60	6
7	175	7
8	255	8
9	285	9
10	302	10
11	307	11
12	310	12

The difference in these values lies in the fact that in the early morning and late afternoon the sun's rays traverse a greater distance through the atmosphere before striking the earth's surface than they do during midday. As a result a greater amount of energy is absorbed by the atmosphere. No account is taken as to the condition of the sky near the earth's surface, and these figures represent only one day of the whole year.

The second method (8) makes use of a fictitious temperature called the "solar temperature difference," which permits the use of an equation identical in form to that used to compute heat flow due only to an air temperature difference, the formula being:

$$Hs = A\ U\ Ds \qquad \text{Eq. 11}$$

where Hs = the excess solar heat gain, B.T.U./hr.

A = the area of exposed surface, sq. ft.

U = over-all coefficient of heat transfer, B.T.U./hr./sq. ft./°F.

Ds = solar temperature difference °F.

When a roof surface is exposed to solar radiation, the temperature of the outside surface is always higher than that of the surrounding air. Therefore, solar radiation is responsible for all heat flow through the structure, and the outside air tends only to take heat away from the surface. As a result there is no heat flow due to the air temperature difference existing across the structure. However, if a certain amount of heat, equal to the amount which would flow through the structure due only to the air temperature difference, or the condition when the structure is shaded from solar radiation, were subtracted from the total solar heat gain, the part remaining would equal Hs, called the excess solar heat gain. To compute this, tables are necessary to determine the factor called the solar temperature difference. This has been done (8) by suitable equations, but several empirical factors were necessarily substituted to allow for the character of surface, the condition of the sky, the air temperature, etc. The purpose of this method is to do away with the nuisance of first having to separate the various areas of a building according to whether they were exposed to solar radiation or just an air temperature difference; so if the surface becomes exposed to solar radiation, it is necessary only to add a certain quantity of heat. When computed by the first method, it is necessary to compute the total solar heat gain and subtract from this the original heat gain due to the air temperature.

Since using either of the above formulae requires certain factors the values of which, while varying erratically under actual conditions, have been determined quite empirically, a more accurate method to measure the effect of solar radiation was felt essential. To measure the amount of impinging radiation striking a surface on the earth for all conditions of weather, an Eppley pyrheliometer and a Leeds and Northrup recording potentiometer to make a continuous record of the solar intensities were used. Another instrument called a Pyranometer was borrowed from the Smithsonian Institute.

Wind velocity determination. Another environmental factor, a measurement of which was essential for a thorough analysis of this study, is the velocity of the air over the surface of the roof sections.

At the beginning of this study a hot-wire anemometer was used. This instrument was placed on the roof surface with leads running to the heater current and the potentiometer. Readings were taken at small intervals of time to determine the air velocity.

The air velocity over a surface depends upon a number of factors, the most important of which are: (1) the direction and amount of wind at that location, (2) eddy currents set up around a structure. (3) natural convection currents which take place as a result of the air being heated from the surface, (4) differences in the frictional resistance offered by the different roof surfaces to the flow of air across them and for the different directions of air flow across them, and (5) the angle which the roof makes to the horizontal. Since all of these factors are so interrelated and so different in their effects, it would be exceedingly difficult to determine accurately their combined results for each of twenty different roofs at a given time. To measure the environmental factor most influential for these individual velocities, it would appear that if an over-all wind velocity measurement were determined at the location of the testing apparatus a measurement of this factor on the velocity of the air over each section of the roof would be determined. To do this a cup anemometer was employed, being located at the site of the testing apparatus.

With the use of this instrument the total amount of wind passing over the test-house site could be determined by a recorder or by reading the integrating scale on the anemometer at known time intervals. This same measurement was found almost impossible to make with the hot-wire anemometer that was originally used.

Temperature gradients for different roof sections under the same environmental conditions. There are several methods of measuring the abilities of different roof sections with regard to their insulation properties that would afford either a direct comparison of the structures one with the other or an absolute indication of their resistances to heat flow. The conventional method would be to describe the physical properties of a structure on an absolute basis or according to an accepted standard scale. To do this for heat flow through a structure the standard scale or measuring device would be the value of the over-all heat conductivity coefficient U. This well known and descriptive term would directly and with a fair degree of accuracy compare a number of sections for conditions which existed when the structures being compared are subjected to only one variable, that of the air temperature difference across the structure. If, however, this structure were exposed to intense solar radiation, the over-all conductivity coefficient if used with the existing air temperature difference across the structure would not only give very inaccurate results as to how much heat would flow through the structure but also in several cases it would cease to be a correct indication of the relative resistances of the structures under comparison.

This may be clarified by considering the following practical illustration. Consider two roof sections, one consisting of corrugated sheet steel on nailing strips, and another corrugated sheet steel roof under which is 3 5/8 inches of "loose-fill" insulation. For a set of conditions existing in a laboratory, or when the gain of heat from impinging radiation is a minimum, a measure of the amount of heat traveling through a section may be accurately determined, and the over-all conductivity coefficient, U, may be directly computed by equation 1 for each of the two roof sections. The coefficient U for the roof sections for convenience will be assumed to be eight and one for the first and second roof sections, respectively. For this set of conditions the relative resistance of the insulated section is eight times that of the uninsulated section. It is quite probable that one-half the resistance of the single sheet steel roof is included in the value of the outside surface conductance coefficient, f_o, in equation 2, while for the insulated roof section approximately 1/30 of the total resistance is offered by the outside surface conductance coefficient. Now, if both roofs were exposed to intense solar radiation, the surface temperatures of each section would immediately become higher than the outside air, resulting in the loss of f_o in equation 2. It is quite obvious according to equation 2 with C equal to infinity for sheet steel that only one-half of the total original resistance remains active for the uninsulated section while 29/30 of the total original resistance remains active for the latter section. This makes the resistance of the insulated section, roughly, fifteen times greater than the resistance of the uninsulated section, or the insulated section in this new set of conditions is relatively almost two times better than it was for the original conditions.

There are other factors which enter into this situation under actual conditions, such as: (1) the insulated section will build up higher surface temperatures which make a greater potential for heat flow than exists for the uninsulated section; (2) the insulated section has considerable heat capacity while the other has practically none; (3) due to the higher surface temperature of the insulated section there is more heat lost from it to the outside air; this assumes the same surface characteristics for each roof, which makes for equal amounts of heat absorption.

In light of the above discussion it is obvious that the over-all conductivity coefficient is not an absolute indication of the relative resistances of different sections for the range of conditions encountered when these sections are exposed to typical outside weather conditions in Iowa.

Practically the only method to directly analyze the heat flow resistance of various roof sections would be one which would require heat flow meters on each surface of the section, to know what actually happened would require heat flow meters within the roof section. Since heat flow meters were not available at the present stage of the study, the procedure considered next best was followed.

If the temperatures are accurately determined at the surface of each material in a roof section and of the outside and inside air, there is obtained a direct measure of the potential for heat flow between any two points of known temperature throughout the roof section. Further, for conditions of steady heat flow, heat flows through each part of the section at the same rate. The temperature gradient would then indicate directly the relative resistances of the various parts of the roof section. Also, if the temperature gradients were obtained for a number of different sections at a given set of environmental conditions, a direct comparison of the several different sections is possible along with a direct comparison of the various materials within each section.

For unsteady heat flow temperature gradients obtained for all the sections under the same set of environmental conditions do indicate the actual conditions existing in each section with regard to potential for heat flow. To find the actual amount of heat flow would necessitate knowing the resistance of each homogeneous material contained within the section and the surface film resistances of both surfaces. One method of doing this will be developed later in this analysis.

It should be emphasized that, for the above analysis to be valid, the temperatures of the outside surface, the outside air and the inside air must be accurately determined. The outside surface temperature is a very important measurement, since it is a measure of the over-all effect of the environmental factors upon a given roof section and is a direct measure of potential setup for heat flow through this section. The outside temperature would tend to be fairly constant over the several sections if measured at a sufficient distance from the surface. The inside air temperature would depend upon two factors: (1) the amount of heat in an airtight compartment beneath the roof section, and (2) the specific heat of the compartment. If, therefore, the specific heat of each compartment for the several roof sections is the same, for purposes of comparison the second factor may be called a constant and set equal to one.

Air temperature of standard heat storage. In view of the last statement it is seen that if the air or compartment temperatures of equal heat storage units beneath the roof sections to be compared are measured throughout the cycle of a day, a relative measure of the amount of heat entering and leaving each roof section is obtained. In the practical application it is the resulting temperature of the inside air for the various roof sections that is of major concern, which value would be given by these compartment air temperatures.

For winter weather conditions

Determination of heat flow through roof sections. A measurement of the potential for heat flow under identical environmental conditions for different roof sections offers only a direct relative comparison of the sections. Therefore, to measure the absolute resistance of a structure a direct determination of heat flow is essential. For clearness in analyzing this problem it is helpful to consider heat flow as comparable to the flow of electricity. The equation relating the fundamental factors which affect the flow of current in a wire is:

$$E = I R_e \qquad \text{Eq. 12}$$

where E = the potential producing the current flow, or the potential difference between terminals

I = the current flow, or the quantity of electricity per unit time

R_e = the resistance to the current flowing

This same law holds for heat flow through a material, namely:

$$T = H R \qquad \text{Eq. 13}$$

where T = the potential to heat flow or the temperature difference $(t_1 - t_o)$

H = the heat flow, or the quantity of heat per unit time

R = the resistivity, or the resistance to the heat flowing

This equation is commonly used in the following form:

$$H = T/R \quad \text{or} \qquad \text{Eq. 14}$$

$$H = U T \qquad \text{Eq. 15}$$

where $U = 1/R$

Expressing equation 15 as $U = H/T$, it is seen that U has the dimensions, amount of heat, B.T.U./hr./sq. ft., per °F. temperature difference. Expressing equation 14 as $R = T/H$, R is the temperature difference required between two points to maintain a heat flow of one B.T.U./hr./sq. ft.

In the above equations if two of the terms are known, the third may be solved for directly. Therefore, if the heat flow is measured, the resistances may be calculated. Several methods may be used to secure the essential information to solve the above equation. However, in the type of setup used for this study only two methods appear to be practical: (1) the use of a heat flow meter, and (2) measuring directly the amount of heat lost by knowing the input. Since heat flow meters were not available, the only feasible method was to supply a measurable amount of heat into the compartment of each roof section. The most convenient way to do this would be to supply heat in the form of electrical energy. Approximate heat losses could be calculated by assigning a heating duty to be maintained across the sections and computing the over-all heat flow coefficients for the various sections from values assigned by various other investigators.

Preliminary calculations showed that the input into each compartment varied between 60 and 300 watts to establish the proper heating duty, or the desired air temperature difference across the wall. Mazda incandescent lamps appeared to be the most feasible type of heating unit for the size required. A light bulb at the temperature of 4500°F. gives off its heat energy in the following ways (20):

8 percent of total energy is conducted along the leads
86 percent of total energy is radiated as infra red rays
6 percent of total energy is light radiation

This shows that the quality of heat from a light bulb approaches closely that of a hot body at nonvisible temperatures.

If the inside air temperatures of the compartments were not maintained at the same value, Grieg in a similar study (10) has found that ..."This temperature difference was not found to have any appreciable effect on the value of K.", or U in this study. However, in a theoretical consideration of this problem, a change of the inside air temperature, or the mean temperature would make for a variation in the value of U. Therefore, for accurate work, the mean temperature should have a small variation for the roof sections under comparison.

<u>Computation of over-all conductivity coefficients</u>. Using the following equation,

$$U = \frac{\text{Watt-hrs. input/hr. to compartment} \times 3.413}{A\,(t_i - t_o)} \qquad \text{Eq. 16}$$

with proper allowances made for the heat flowing through the floor of each compartment and through the partition walls, the coefficient U may be computed from experimental data.

Conclusions

1. The environmental factors affecting heat flow through a roof section should be determined accurately if the resistance offered by a structure is to be analyzed with a reasonable degree of certainty.
2. The conventional method of heat flow computations was

found inadequate for the range of conditions existing under summer weather conditions in Iowa.

3. Heat flows through any structure by a combination of all three methods of heat flow, radiation, conduction and convection.
4. Equations have been established to compute the heat flow by each of these three methods.
5. There is an unequal change in the rate of heat flow for the three methods when temperature differences vary. Each has been found to vary as follows:

   Conduction - directly as the 1st power of the temperature difference
   Convection - directly as the 5/4 power of the temperature difference
   Radiation - directly as the 4th power of the temperature difference ?

6. One of two methods are generally used at the present time to calculate the maximum probable heat gain of a building due to solar radiation.
7. Each of these methods demands more accurate information to make their use more versatile.
8. The impinging radiation intensity, wind velocity, and outside air temperature are the essential environmental factors to be measured.
9. Temperature gradients of all the roof sections under study, if obtained for the same set of environmental conditions, offer a basis for directly comparing them as to their ability in stopping heat flow from impinging radiation.

10. The outside surface temperature of a given structure and a given set of conditions indicate directly two things: (1) the potential for heat flow through the structure, and (2) the over-all effect of the environmental factors.
11. The angle which the wind makes to a surface may be neglected as a factor, but an indication of the wind direction is essential.
12. Relative humidity may be neglected as an influencing factor on heat flow by transmission.
13. The resistance of a structure may be determined in absolute terms by experimentally finding any two of the three factors in the fundamental heat flow equation, $T = H\ R$.

INVESTIGATION

Part of the work in this section logically would be listed under the heading EXPERIMENTAL. However, much of this section is devoted to a theoretical study which would not be listed in the section entitled ANALYSIS OF PROBLEM. Therefore, the term INVESTIGATION is used, which, in the author's opinion includes both the theoretical and experimental studies.

Measurement of Solar and Sky Radiation

For many years the only measure relative to solar radiation was the duration of the sunshine. Obviously, this record was as incomplete as would be a rainfall record if only the duration was measured and not the intensity.

Fundamental principles involved

The intensity of the total radiation impinging upon a surface exposed to the heavens may consist of one or a combination of the four following classifications of impinging radiation: (1) the intensity of radiation coming directly from the sun, (2) the intensity of diffused radiation coming from a clear or partly clouded sky, (3) the intensity of diffused radiation from a gray sky, (4) the intensity of diffused radiation from surrounding trees and buildings.

For all practical purposes in this study, since the location of the test structure is in the open, the fourth classification is negligible. The third classification occurs when the sun and blue sky are completely obscured by clouds. The condition of this sky varies considerably, but the characteristics of the constituent parts may be treated alike for the different degrees of cloudiness as long as the sun is completely obscured. There are two general situations possible for the second classification: (1) a perfectly clear, or a blue sky, and (2) a partly clouded sky but one which does not obscure the sun. For a surface normal to the sun's rays the intensity of this type or radiation also varies erratically from hour to hour and for different days as a result of weather conditions or when they occur in the yearly cycle. The principal factors making for this difference are the moisture and dust content of the air between the surface and the sun and the distance the sun's rays come through the atmosphere. To determine the vertical component for other plane surfaces, the angle of incidence which the sun's rays make to the surface must be determined.

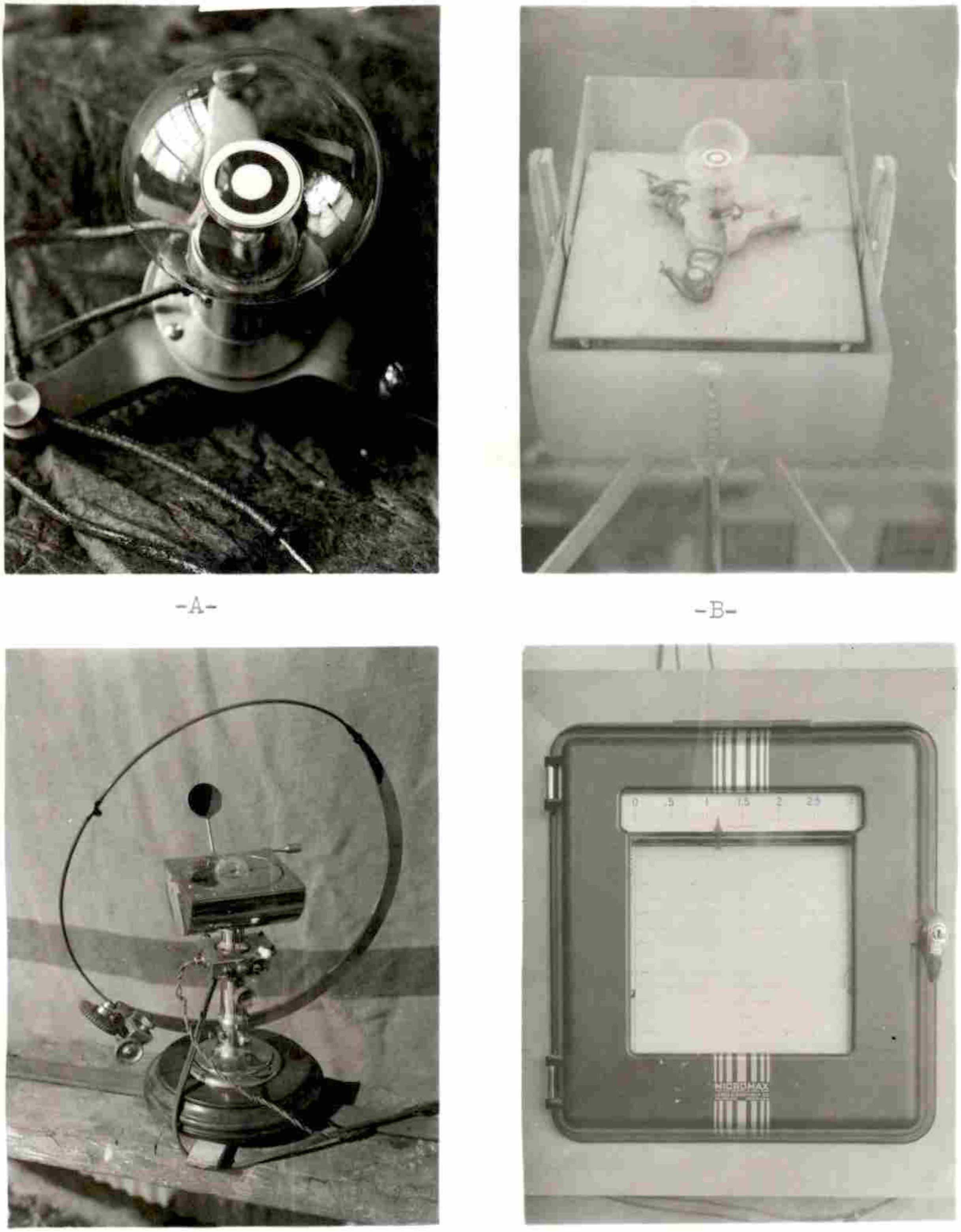
There are several kinds of measurements to be made for a complete analysis of the impinging radiation, namely: (1) the duration of direct solar radiation, (2) the quality of the radiation, or its relative intensity in different parts of the spectrum, (3) the intensity of direct solar radiation, (4) the intensity of total radiation (direct plus diffuse) striking a surface, (5) the intensity of diffuse radiation.

Although sunshine recorders for keeping records of the duration of solar radiation are made and used by weather bureau stations, such a measure is not essential for this study. Therefore this information was not obtained accurately. However, a record of the intensity of radiation would be an indication of the hours of sunshine.

The quality of solar radiation or the intensity of radiation for different parts of the spectrum and for different distances which the solar rays travel through the atmosphere has been carefully determined by other investigators. In this study the primary concern is with just the total amount of energy, the quality of the energy being a secondary factor. To obtain the intensity of direct solar radiation would require the use of an instrument designed primarily for that purpose, or one which would always be in a plane perpendicular to the sun's rays, thus measuring just the intensity of the sun's radiation. With the use of an instrument which reads the total radiation (direct plus diffuse) on a horizontal surface it would require a separation of these two combined factors, one being the vertical component of the direct or solar radiation. This component could be converted to a plane normal to the sun's rays and from there could be taken to any other plane surface by means of trigonometric calculations. The intensity of total radiation is usually obtained by an instrument located in a horizontal plane which is exposed to the complete hemisphere of the heavens. The intensity of diffuse radiation can be measured on a clear day by blotting out the sun with a small opaque object located at a distance from the instrument which would cut out little of the sky radiation.

Methods used

In this study two instruments were used that were capable of measuring total radiation intensities of solar spectrum wave lengths. The first instrument, Fig. 2-C, Pyranometer S. I. #8 was loaned through the courtesy of C. G. Abbot, Secretary of the Smithsonian Institution. This instrument operates on the electric compensation principle. The receiving element consists of two strips of blackened maganin, each exposing surfaces 6 mm. long and 2 mm. wide. These strips are mounted on two small copper blocks, one of which is 10 times thicker than the other, and are located in the surface plane of a nickel plated copper block. These two strips along with their attached copper blocks are electrically insulated from each other and from the other surrounding parts by means of thin vertical separating strips of mica. Electrical conductors run from these copper blocks on which the maganin



-A- -B-

-C- -D-

Fig. 2. Instruments for measuring solar and sky radiation

strips are mounted to a pair of binding posts on the outside of the instrument. Appropriate resistances are placed in the two circuits so that, even though one copper block is ten times larger than the other and, thus, has a correspondingly smaller resistance to flow of current, compensation is provided by these resistances so that the current divides in the proper proportion between the two copper blocks to heat them at exactly the same rate. Thermocouples are arranged with their alternate warm and cold junctions respectively being placed so as to indicate the difference in temperature between the two copper blocks.

The principle of operation may now be explained. Radiation falls simultaneously on the two maganin strips giving the same quantity of heat to each, but since one is ten times larger than the other, its corresponding temperature rise will be smaller. Therefore, a deflection of the galvanometer connected across the thermocouples will occur. An equal deflection is again produced, after the strips have been shaded from any outside radiation, by passing a suitable amount of electrical current through the copper blocks, which current also gives the same amount of heat to each block. With the above conditions having been fulfilled, the electric current supplied the same amount of energy to the copper blocks as did the absorbed radiation which fell upon the maganin strips. With the current being accurately measured and all the constants of the instrument being determined, the amount of energy can be computed and converted into desirable units of heat measurement (2).

The receiving elements are covered with a hollow hemispherical screen of ultra-violet crown glass 25 mm. in diameter and 2 mm. thick, whose purpose it is to admit scattered solar radiation but to prevent the exchange of long wave radiation from the receiving elements of the instrument back to the sky. A hollow hemispherical shutter is provided to shade the receiving elements from the sun and sky. This permits a zero reading on the galvanometer.

This instrument may be used in a horizontal position or at any other angle to the horizontal which it may be placed. It may be used to measure both solar and sky radiation, or just sky radiation through the use of a small opaque object cutting off the direct rays from the sun. It may also be used for measuring nocturnal radiation to the sky by removing the hemispherical glass screen (1).

This instrument is a direct reading instrument and requires considerable skill on the part of the observer to secure accurate readings. It also requires the constant attention of two parties to secure readings, since one party has to open and close the shutter at the command of the operator reading the galvanometer. However, it was used to obtain the different readings listed above, the results for which are shown in Table VI.

To obtain a record of the intensity of the total radiation impinging upon a horizontal surface, an Eppley pyrheliometer with a Leeds and Northrup recording potentiometer was were employed; see Fig. 2-A,B,D. The Eppley pyrheliometer (29) consists of a thermopile hermetically sealed in a glass bulb which has been thoroughly dried out and partly evacuated. The thermopile consists of 10 couples of gold-palladium and platinum-rhodium wire. Alternate junctions are fastened to rings coated with soot and magnesium oxide. The principle of operation now seems apparent. (29. p. 17)- "These blackened and whitened surfaces absorb long wave radiation equally well, but the magnesium oxide has a high coefficient of reflection for radiation having the wave length of solar radiation. Therefore, when exposed to solar radiation, the two rings of this pyrheliometer develop a marked temperature difference, and the resulting electric current"..., for this instrument shows the e.m.f. of 1.51 millivolts for radiation intensity of 1 gram calorie per minute per square centimeter of surface. It has been assumed that the relation between radiation intensities and e.m.f. is rectilinear. The maximum probable error of this assumption as reported by the U. S. Weather Bureau would be plus or minus 1.5 per cent cal. min.$^{-1}$ cm.$^{-2}$ in radiation intensities varying from 0.25 to 1.5 cal. min.$^{-1}$ cm.$^{-2}$.

Table VI. Pyranometer Readings

Facing	Date: Time	Galvanometer Defl. cm.	Object	Current: Amps. C^2	Resistance Ohms	Pyranometer: g. cal. min.$^{-1}$ cm.$^{-2}$	Pyrheliometer: Horizontal Sun and Sky g. cal./min. per cm.^{2}	Percent of Horizontal Sun and Sky Reading
	10-27-38*							
Hor.	10:40 a.m.	22.8	S & S		590	0.678	0.695	-
	"	21.9	C	.0408	590			
Hor.	10:52 a.m.	24.6	S & S		590	0.735	0.745	-
	"	21.8	C	.0408				
Hor.	11:28 a.m.	14.2	Sky		170	0.177	0.794	22.3
	"	13.3	C	.0104				
Hor.	11:30 a.m.	13.8	Sky		170	0.176	0.806	21.8
	"	13.0	C	.0104				
	1-5-39*							
E. 45°	10:57 a.m.	32.8	G.Sky		50	0.112	0.165	68.0
	"	39.0	C	.00832				
W. 45°	11:00 a.m.	29.6	G.Sky		50	0.134	0.165	81.0
	"	29.3	C	.00832				
S. 45°	11:07 a.m.	36.0	G. Sky		50	0.155	0.198	78.5
	"	30.9	C	.00832				
N. 45°	11:10 a.m.	34.5	Sky		50	0.1521	0.166	91.0
	"	30.0	C	.00832				
W. Vert.	11:14 a.m.	23.6	G. Sky		50	0.1075	0.198	54.2
	"	18.9	C	.00521				
E. Vert.	11:17 a.m.	22.9	G. Sky		50	0.0945	0.198	48.0
	"	18.9	C	.00521				
S. Vert.	11:20 a.m.	24.1	G. Sky		50	0.1000	0.22	45.5
	"	18.8	C	.00521				
N. Vert.	11:23 a.m.	21.3	G. Sky		50	0.0943	0.198	47.6
	"	18.8	C	.00521				

TABLE VI. Pyranometer Readings
(Cont.)

Facing	Date: Time	Galvanometer Defl. cm.	Object	Current Amps. C^2	Resistance Ohms	Pyranometer g. cal. min.$^{-1}$ cm.$^{-2}$	Pyrheliometer Horizontal Sun and Sky g. cal./min. per cm.^{2}	Percent of Horizontal Sun and Sky Reading
	1-5-39*							
Hor.	11:30 a.m.	31.8	G. Sky		120	0.249	0.238	-
	"	26.5	C	.0140				
	1-10-39*							
Hor.	11:15 a.m.	15.9	S & S		520	0.554	0.594	-
	"	16.2	C	.0354				
Hor.	11:20 a.m.	11.1	Sky		150	0.0927	0.562	16.5
	"	14.8	C	.00775				
Hor.	11:25 a.m.	8.35	Sky		150	0.107	0.604	17.9
	"	10.4	C	.00775				
S. 45°	11:30 a.m.	13.7	S & S		1,420	1.26	0.604	209.0
	"	17.7	C	.102				
S. 45°	11:35 a.m.	14.0	Sky		150	0.157	0.604	25.0
	"	11.0	C	.00775				
S. 45°	11:40 a.m.	15.2	S & S		1,420	1.41	0.662	213.0
	"	17.5	C	.102				
N. 45°	11:45 a.m.	13.0	Sky		150	0.132	0.72	18.3
	"	12.2	C	.00775				
E. 45°	11:50 a.m.	12.6	S & S		400	0.349	0.662	52.6
	"	16.7	C	.0290				
E. 45°	11:55 a.m.	20.9	Sky		150	0.256	0.662	38.6
	"	12.0	C	.00925				
	1-19-39*							
Hor.	9:40 a.m.	26.6	S & S		170	0.375	0.378	-
	"	24.9	C	.0231				

Table VI. Pyranometer Readings
(cont.)

Facing	Date: Time	Galvanometer Defl. cm.	Object	Current Amps. C^2	Resistance Ohms	Pyranometer g. cal. $min.^{-1}$ cm^{-2}	Pyrheliometer: Horizontal Sun and Sky g. cal./min. per $cm.^2$	Percent of Horizontal Sun and Sky Reading
	1-19-39*							
S. 45°	11:33 a.m.	29.1	S & S		770	1.23	0.662	186.0
	"	28.2	C	.075				
N. 45°	11:35 a.m.	11.6	S & S		170	0.134	0.662	20.2
	"	21.2	C	.0154				
S. 45°	3:25 p.m.	17.0	Sky		170	0.188	0.304	61.8
	"	15.4	C	.0104				
S. 45°	3:27 p.m.	22.6	S & S		570	1.13	0.298	378.0
	"	18.2	C	.0575				
Hor.	3:45 p.m.	14.2	Sky		120	0.124	0.232	53.4
	"	18.0	C	.0098				
Hor.	3:50 p.m.	21.3	S & S		120	0.183	0.199	-
	"	18.3	C	.0098				
	1-20-39*							
Hor.	8:30 p.m.	-	-	.0226	-	0.344	-	-
S. 45°	8:35 p.m.	-	-	.0135	-	0.205	-	59.4
N. 45°	8:40 p.m.	-	-	.0092	-	0.145	-	42.1

* 10-37-38 Clear with bright sun.
* 1- 5-39 Sky was completely overcast with clouds - clouds cleared slightly toward noon.
* 1-19-39 Slightly cloudy, except 11 a.m. to 4 p.m. which was clear.
* 1-20-39 Night reading with clear sky and with few stars.

This instrument is mounted on the platform of a windmill tower, Fig. 2-B, 100 feet above the ground, which location affords a clear and unobstructed view of the horizon in all directions. It is impossible to use this instrument for measuring nocturnal radiation because the glass bulb, which is not removable, absorbs the long wave radiation being emitted from the elements and thus tends to keep them at the same temperature. Leads from the instrument run to the recording potentiometer, Fig. 2-D, located in the Utility Room of the Agricultural Engineering Laboratory. Permanent records were started for this instrument on September 20, 1938, and shall be continued indefinitely. Only one type of reading has been made so far, that of the total radiation (direct plus diffuse) striking a horizontal surface.

Results

Fig. 3 shows the records of total radiation striking a horizontal surface for typical days so far encountered in the observations. The essential information is typed on each chart. The scale range of the recording potentiometer is from 0 to 3 millivolts as shown on the charts, and these curves indicate directly the e. m. f. produced by the thermopiles, which values must be divided by a constant 1.51 to obtain the values in the units, g. cal. min.$^{-1}$ cm.$^{-2}$. These are the values for a horizontal surface and since in this

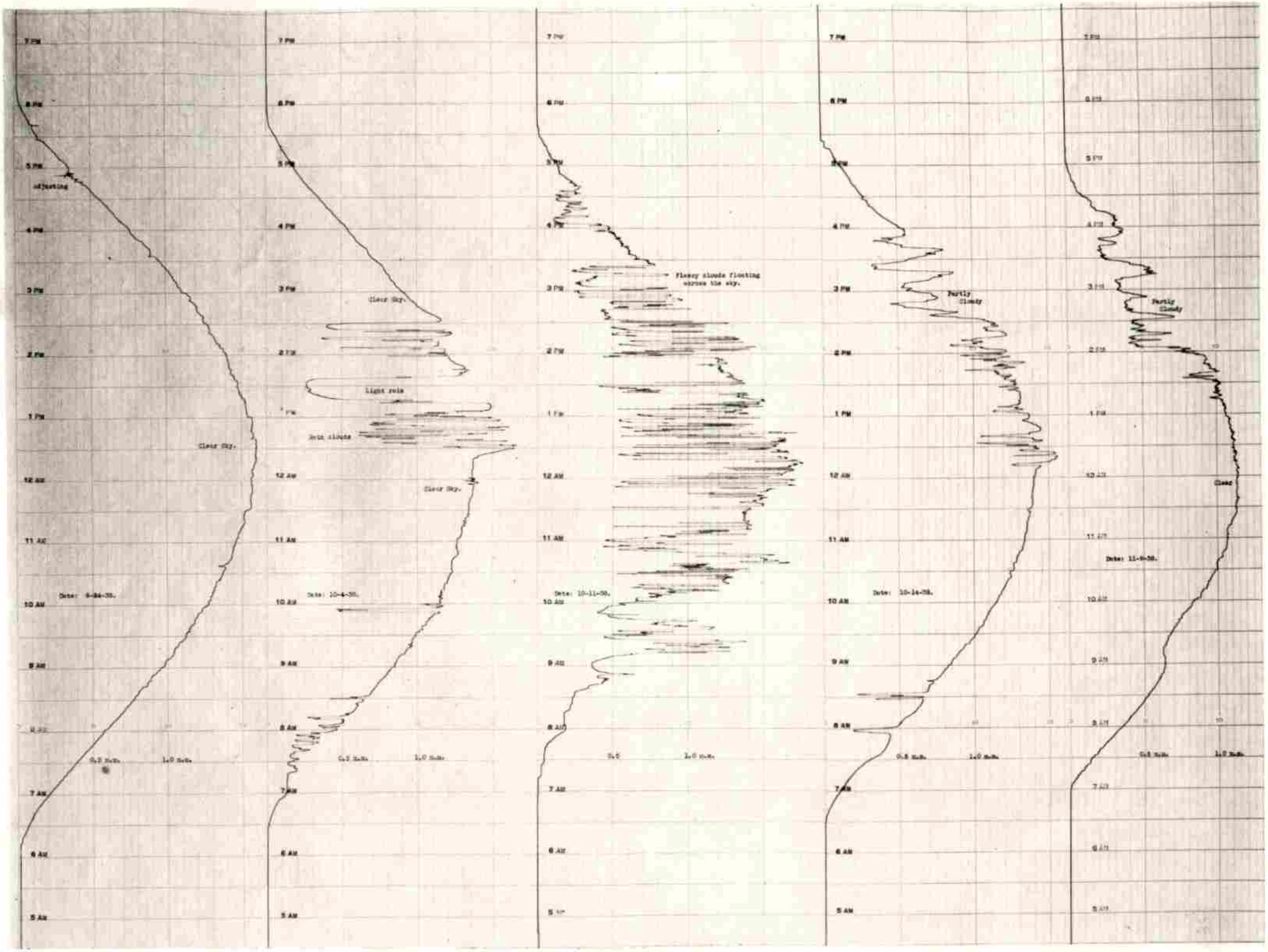


Fig. 3. Graphic record of solar and sky radiation intensities at Ames, Iowa

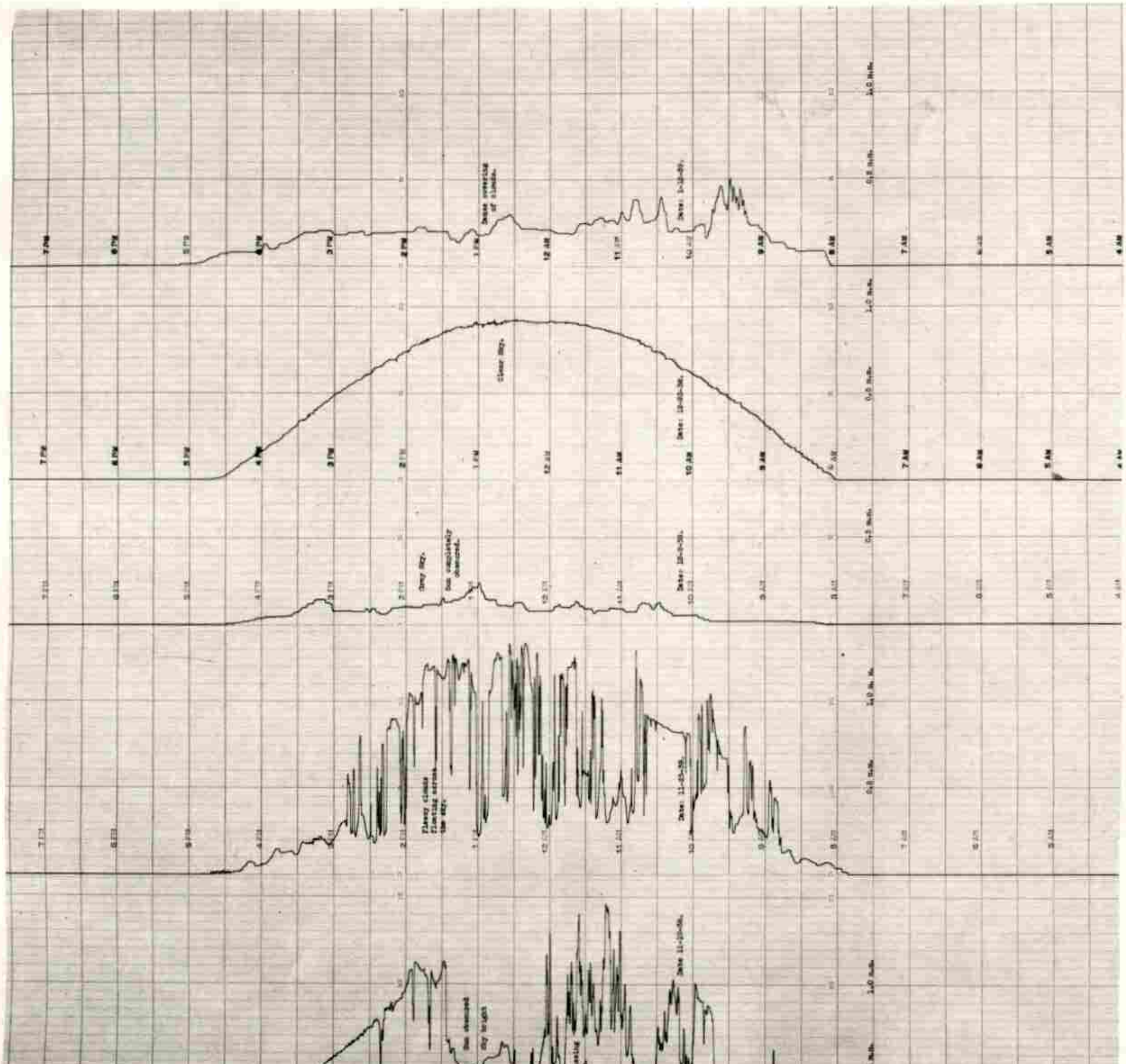


Fig. 3. (Cont.)

study the normal intensities for other plane surfaces facing the cardinal points of the compass are desired, it is necessary to find the components of these values for other nonhorizontal surfaces. To do this demands a careful and rather lengthy procedure.

The direct radiation intensities for surfaces not horizontal depend directly as the measured horizontal intensity of the direct rays and inversely as the difference between the size of the angles of incidence which the sun's rays make with the normals of the two surfaces, respectively. The diffuse radiation intensities for surfaces not horizontal depend directly upon the intensity of the sky radiation falling normally upon the surfaces. The amount of sky radiation falling normally upon any surface depends upon: (1) condition of the sky as to cloudiness or blueness; (2) the angle which the normal to the surface makes with a vertical line, which passes through the zenith; (3) the angle which the normal to the surface makes with the sun at a particular time.

Therefore, it becomes necessary to separate the direct from the diffuse radiation. This may be done for a horizontal surface with the following equation:

$$Q_h = \frac{Q_n \times \text{Sin } H}{r} \qquad \text{Eq. 17}$$

where Q_h = total (diffused + direct radiation

received on a horizontal surface

Q_n = the direct radiation intensity measured perpendicular to the sun's rays

h = the altitude of the sun

r = the ratio of the vertical component of direct solar radiation to that of the vertical component of the total radiation (sun and sky or direct plus diffuse)

Transposing, $Q_n = \frac{r\,Q_h}{\sin h}$

Q_h is measured directly. Sin ~~a~~ h may be obtained from Fig. 4 and a table of trigonometric functions. Table VII (18) gives the values of r for the different zenith distances of the sun (zenith distance is an angle equal to the complement of the altitude angle of the sun). They were obtained at Lincoln, Nebraska, Lat. 40° 50' N., Long. 96° 41' W. over a considerable period of time by using two instruments lying in a horizontal plane, one which was exposed to both sun and sky radiation, the other which was shielded from the sun or which measured just sky radiation. For obvious reasons they are valid for only clear sky conditions.

Table VII. Ratio of the Vertical Component of Direct Solar Radiation to the Total Radiation Received on a Horizontal Surface

Zenith distance of sun:-	30.0°	48.3°	60.0°	66.0°	70.7°	73.6°	75.7°	77.4°	78.7°	79.8°
r:	.85	.84	.81	.79	.76	.73	.70	.67	.65	.63

The difference between Q_h and the vertical component of Q_n is the horizontal intensity of the sky radiation. The author has been able to find no work which has been done to measure the relative amounts of the complete spectrum radiation intensities that come from various points in the sky hemisphere for the various conditions affecting these intensities. However, other investigators (16) have reported the sky illumination intensities for the various positions of the sun in the sky and for different conditions of the sky for a year's cycle. They also gave figures and tables showing the sun and the total sun and sky visible radiation, or illumination intensities received on vertical planes facing the eight points of the compass for all hours of the day and all days of the year. In another report (17) Table VIII was given showing the illumination equivalent of a gram calorie per min. per sq. cm. of total radiation with the sun at different zenith distances. These equivalents were obtained by simultaneous readings from a pyrheliometer and a photometer, both instruments being placed in a horizontal plane. This report further showed that the qualitative changes of the solar and sky spectrums received at the earth's surface due to the sun's rays traveling through greater distances in the atmosphere for greater zenith distances of the sun made it inaccurate to apply Table VIII to correlate directly the visable to the total spectrum of direct or direct and diffuse radiation intensities for other than horizontal surfaces. In other words, this table may be used accurately for only horizontal surfaces.

Table VIII. Illumination Equivalent of a g. cal.min.$^{-1}$ cm.$^{-2}$ of Radiation with the Sun at Different Zenith Distances. Foot Candles, Measured on Horizontal Surface.

Solar zenith distance	25.0°	47.3°	60.0°	67.6°	70.7°	73.6°	75.5°	77.4°	78.7°
Direct	7020	6880	6740	6650	6580	6520	6460	6410	6370
Total	7000	6740	6470	6320	6260	6220	6200	6200	6200

Concerning luminous radiation intensities, studies have shown (13):

1. With cloudy skies the illumination on a vertical surface is practically independent of the orientation of that surface.
2. With a cloudy sky the illumination on a horizontal surface is nearly twice that on a vertical surface, because the region of maximum sky brightness is in or near the zenith.
3. At Washington, the illumination from a clear sky on both horizontal and vertical surfaces varies between 150 and 60 percent of the average values; from a cloudy sky, between 200 and 30 percent. The illumination from a sky partly covered with white clouds is, on a horizontal surface three to four times that from a clear sky; on a

vertical surface, two or three times. With rain falling, the illumination is about half that from a cloudy sky.

Work with the pyranometer on different days gave essentially the following results as shown in Table VI:

1. For a completely clouded sky the radiation for vertical surfaces is essentially the same irrespective of the direction it faces, and equals about one-half the value of the horizontal intensity.
2. Under the same conditions with the sun at a zenith distance of 64° 30' surfaces 45° to the horizontal had intensities equal to 91.0, 68.0, 78.5, 54.2 percent for N.E.S. and W. facing respectively.
3. The total radiation impinging upon a surface not horizontal depends upon a number of factors and varies erratically from that measured on a horizontal surface.
4. A continued study is felt necessary to obtain the essential information concerning the distribution of sky radiation intensities for different positions of the sun in the sky and for various conditions of the sky, the purpose being to supply essential information that will enable an empirical determination of the sky radiation at various points in the sky from a horizontal reading of the total radiation intensity.

For clear sky conditions the results of other investigators appear to warrant the use of equation 17 by which the amount of direct radiation from the sun impinging upon surfaces other than the horizontal can be obtained from one horizontal reading which includes both direct and diffuse radiation. For clear sky conditions this equation also determines the amount of diffuse radiation impinging on a horizontal surface, but as has been shown, necessary information is lacking to permit the translation of this reading to other nonhorizontal surfaces. With the proper factors of translation available for the diffuse radiation, the procedure for finding the total radiation impinging upon any nonhorizontal surface becomes simplified by the use of the curves plotted in Fig. 4 and 5. To facilitate in the use of these curves the following explanation is given.

Let I_p, Fig. 6-A, equal the unit solar heat or direct radiation impinging upon a surface perpendicular to the rays of the sun, B.T.U./hr./sq. ft. of perpendicular surface.

Let I_u equal the unit solar heat impinging upon a surface at any angle with the rays of the sunlight, B.T.U./hr./sq. ft. of surface.

Let i = the angle of incidence

Let h = the altitude of the sun

Let Z = the azimuth angle of the sun (S(0°0') E or W.

It is seen from Fig. 6-A that for any surface I_u equals I_pCos i, and for a horizontal surface Cos i equals Sin h. Therefore to translate either way from I_u to I_p from a nonhorizontal to a horizontal surface the only required factor

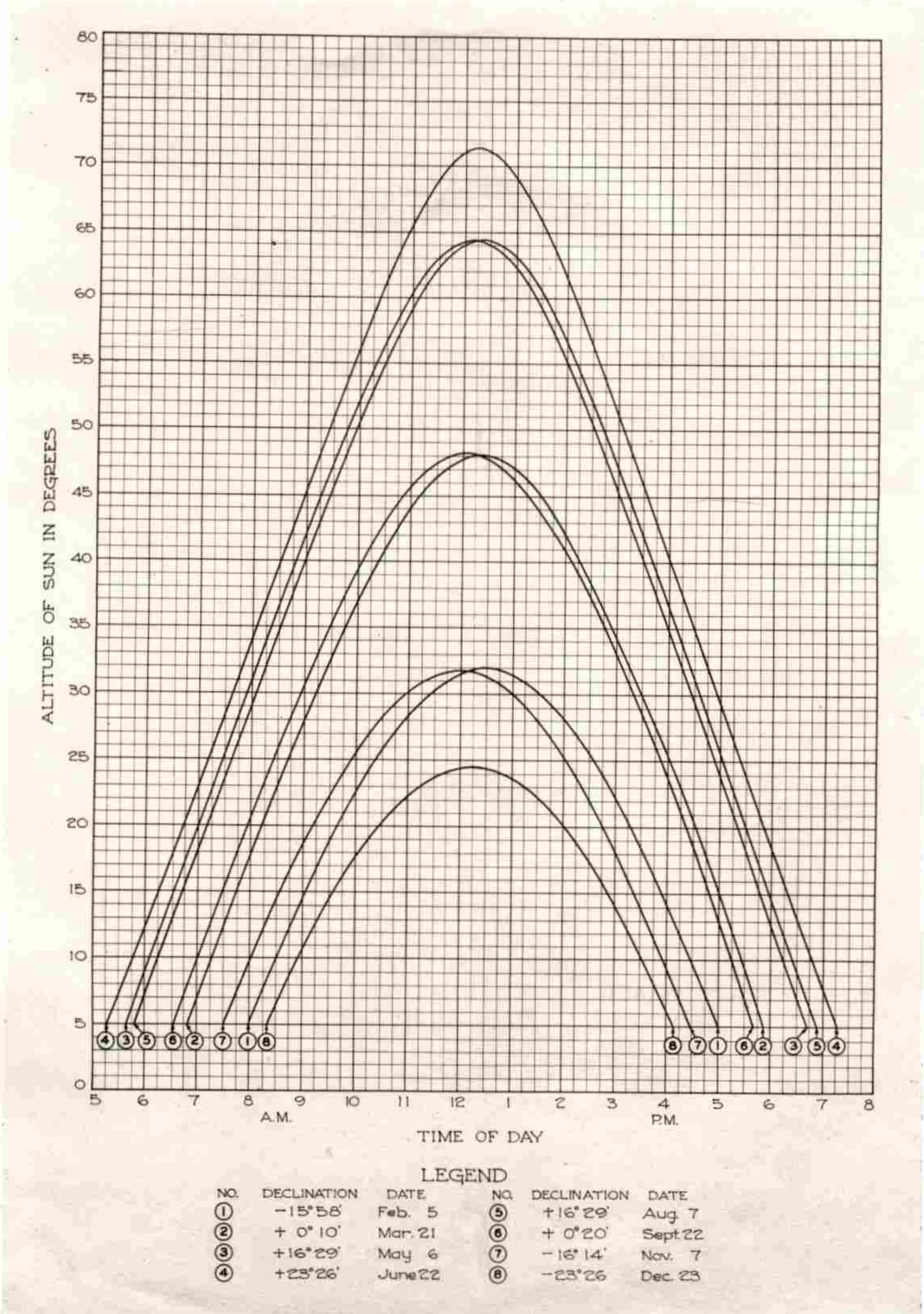


Fig. 4. Curves for finding the altitude of the sun

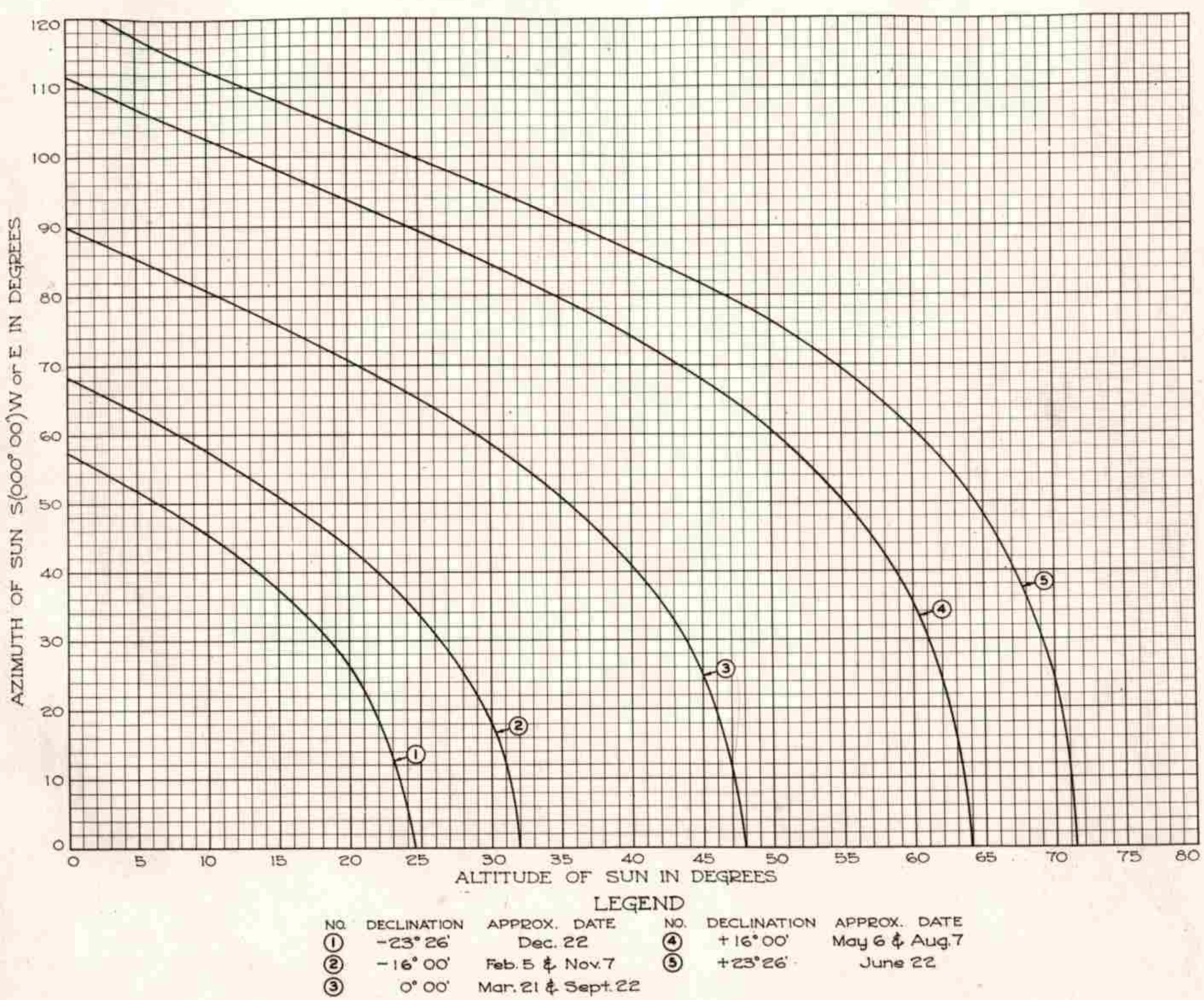


Fig. 5. Curves for finding the azimuth of the sun

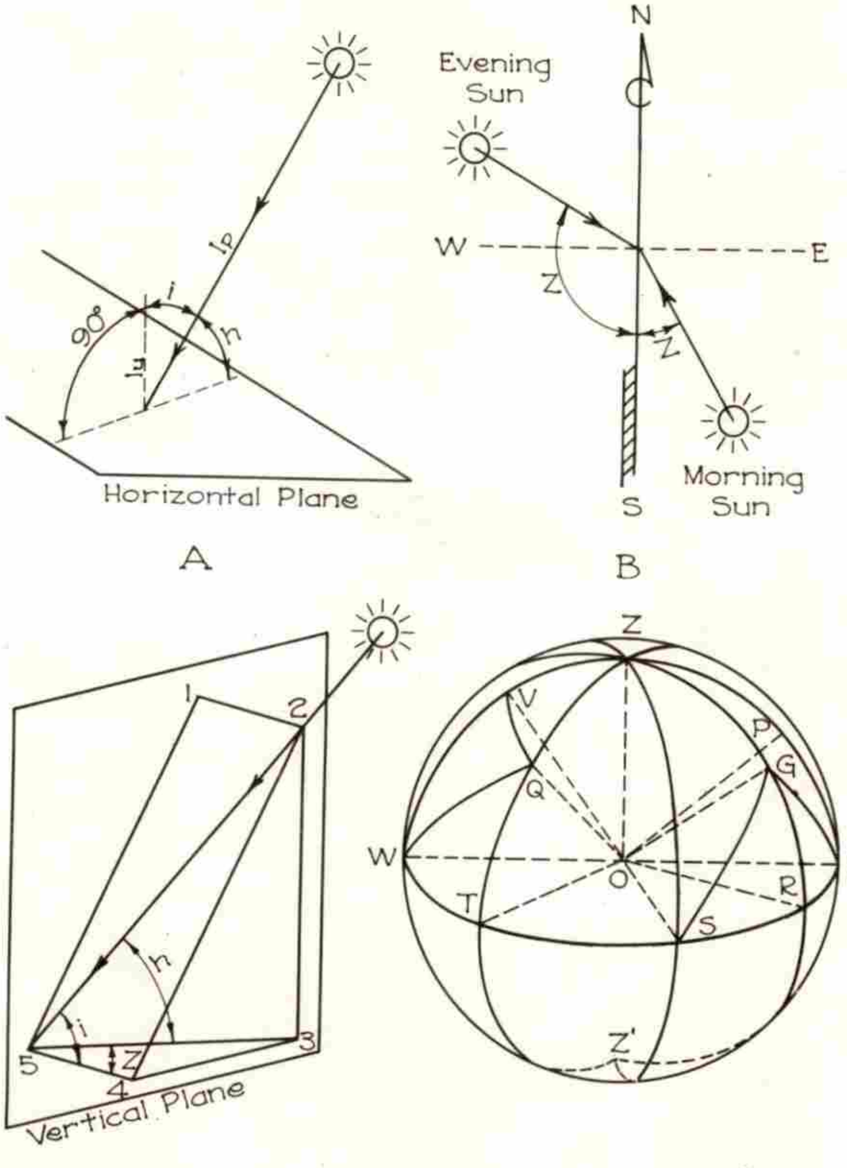


Fig. 6. Diagrams to aid in computing the angle of incidence of sun's rays for any surface

is Cos i.

To obtain Cos i, use is made of a fundamental formula of spherical trigonometry, the derivation of which may be found in any spherical trigonometry textbook, called the cosine-formula, which states:

$$\text{Cos } a = \text{Cos } b \text{ Cos } c + \text{Sin } b \text{ Sin } c \text{ Cos } A$$

By the use of this formula, if two sides, e.g., b and c and the included angle A of a spherical triangle ABC are known, it is possible to find directly the third side a. This is the only set of conditions for which this formula is used in the following calculations. Since both the altitude and azimuth angles must be known to find Cos i, and since the resulting combination of these two values are never the same at a given place on the earth's surface but four times each year, it would be superfluous to show in table or graphic form the values of Cos i for the many different surfaces possible for a yearly cycle of the sun. Therefore, curves are given for finding just the azimuth and the altitude angles for the sun at a given location on the earth for the cycle of a year.

These curves for Fig. 4 were obtained by the use of the cosine-formulae where

a = h = the altitude of the sun

b = ø = the latitude of the place for which the curves were drawn

$c = d$ = the declination of the sun

$A = H$ = the hour angle of the sun

In substituted form this equation reads,

$$\text{Sin } a = \text{Sin } \phi \text{ Sin } d + \text{Cos } \phi \text{ Cos } d \text{ Cos } H \qquad \text{Eq. 18}$$

The location for which these curves were drawn is Ames, Iowa, Lat. N 42° 1.6', Long. 93° 38' W. Curves for eight evenly distributed days of the year were plotted; the altitude for intervening dates can be interpolated. To plot these curves the declinations of the sun for the various dates were obtained from the American Ephemeris for 1938. The hour angle was obtained from the time of day which for Ames is the mean solar time for the 90th meridian west of Greenwich, the equation of time, and the fact that Ames lies 3° 38' west of this meridian. Although these curves were plotted for the year 1938, they may with slight error be used for any year.

To find the azimuth of the sun for the corresponding value of the altitude taken from Fig. 4, use is made of the curves in Fig. 5. The data used for plotting these curves are independent of the results taken from the altitude curves. As indicated in the legend of Fig. 5 curves for finding the azimuth angle of the sun for any hour of the sunlight day for any day of the year are given for dates when the declination of the sun is -23° 16', -16° 0', 0° 0', + 16° 0', and +23° 26', the approximate dates when these declinations occur, being in the same order, Dec. 22; Nov. 7 and Feb. 5; Sept. 22 and March 21; Aug. 7

and May 6; and June 22. Here, again, the azimuth of the sun for intervening dates can be interpolated. These curves are also plotted for Ames. To do this use was made of the cosine-formula where a = d = the angle of declination

b = ϕ = the angle of latitude

c = h = the angle of altitude

A = Z = the azimuth of the sun measured from the north either east or west

In substituted form the formula reads,

$$\text{Sin } d = \text{Sin } \phi \text{ Sin } h + \text{Cos } \phi \text{ Cos } h \text{ Cos } Z \qquad \text{Eq. 19}$$

In plotting the azimuth angles they were translated to read from the south either east or west by subtracting the values from the above equation from 180°.

From the use of this companion set of curves the corresponding altitude and azimuth angles of the sun may be ascertained for any desired time of the year. The next step is to find the angle of incidence which these rays make with a vertical surface facing any one of the four directions or with a surface at any angle to the horizontal facing any one of the four directions. The explanation is limited to just the surfaces facing one of the four directions, although as will become quite obvious, the same procedure holds for any surface.

Referring to Fig. 6-D where O is the observer's position of the earth; WTSE, the plane of his horizon; Z, his zenith; W, S, E, the west, south, and east points of the compass.

G, a given position of the sun in the forenoon, and Q, a given position of the sun in the afternoon. It is seen that for an east vertical wall OG is the path of the sun's rays, OE is the perpendicular to the wall, and the angle GOE or the spherical angle GE represents the angle of incidence of the sun rays to the wall. If sufficient information is known concerning the spherical triangle GZE, angle GE may be found. As stated before, if two sides and the included angle of a spherical triangle are known, the third side may be found by use of the cosine-formula. The angle ZE or any other angle measured from Z on the great circle WZEZ' between Z and E, such as angle ZP, is equal to the angle that an east facing surface makes with the horizontal and is known for the set of conditions under consideration. The angle ZG is the complement of the altitude angle of the sun GR and may be determined from the curves in Fig. 4. The included angle GZE or the angle subtended at O by RE is the complement of the azimuth angle of the sun and may be determined from the curves in Fig. 5. Using the cosine-formula where

$a = i =$ the angle of incidence,

$b = h =$ the altitude of the sun,

$c = E =$ the angle equal to or less than 90° which an east facing surface makes to the horizontal,

$A = Z =$ the azimuth angle of the sun,

the angle of incidence i may be found. In substituted form this formula for an east facing wall becomes,

$\text{Cos } i = \text{Sin } h \text{ Cos } E + \text{Cos } h \text{ Sin } E \text{ Sin } Z$ Eq. 20

This formula holds for all positions of the sun and for any angle which an east wall makes to the horizontal. It should be remembered that for azimuths reading west of south that Z becomes a negative angle and that the Sin of a minus Z is equal to the minus Sin Z.

For a south facing wall the formula in substituted form becomes $\text{Cos } i = \text{Sin } h \text{ Cos } S + \text{Cos } h \text{ Sin } S \text{ Cos } Z$ Eq. 21

where S = the angle which a south facing surface makes to the horizontal.

For a west facing wall the formula becomes,

$\text{Cos } i = \text{Sin } h \text{ Cos } W + \text{Cos } h \text{ Sin } W \text{ Sin } Z$ Eq. 22

where W = the angle which a west facing surface makes to the horizontal,

For a north facing wall the formula becomes,

$\text{Cos } i = \text{Sin } h \text{ Cos } N + \text{Cos } h \text{ Sin } N \text{ Cos } Y$ Eq. 23

where N = the angle which a north facing surface makes to the horizontal, and

Y = the azimuth angle of the sun measured from the north either east or west, or $180° - Z$.

For a south facing vertical wall with the sun at G. the angle of incidence is GS; this makes the spherical triangle to be solved GSZ. For a west facing vertical wall with the sun at Q, the angle of incidence is WQ and the spherical triangle is WZQ. For a west facing wall at 30° to the horizontal with the sun at Q, the angle of incidence is VQ, where VZ = 30°, and the spherical triangle is VQZ, etc.

It will be noted for the above four equations that for vertical walls which make a 90° angle to the horizontal, the first term on the right hand side of the equation is zero and that one of the factors in the second term is one. This leaves an equation of only one unknown term containing two factors which can be quickly solved by the use of logarithm tables. To more clearly show the set of conditions existing for vertical surfaces Fig. 6-C is shown, where h is the altitude of the sun; Z is the azimuth angle, the complement of the azimuth, or some other known angle depending upon the direction of facing; and i is the angle of incidence. It is readily seen from this Fig. that,

$$\text{Cos } i = \text{Cos } Z \text{ Cos } h \qquad \text{Eq. 24}$$

since $\text{Cos } h = \frac{5-3}{5-2}$ and $\text{Cos } Z = \frac{5-4}{5-3}$ and in multiplying

$$\text{Cos } i = \frac{5-4}{5-2} = \text{Cos } h \text{ Cos } Z$$

Summary

Since the author feels that his work on this particular part of the study accomplished results only in providing a method of procedure on which further study may follow, there are no definite conclusions of the results. However, a brief summary will assemble the main accomplishments of the study.

1. Impinging radiation upon a roof surface was classified as to source.
2. The several kinds of measurements necessary for a complete analysis of impinging radiation were listed.
3. Two instruments were used to measure the quantity of direct or direct plus diffuse radiation intensities, a pyranometer and a pyrheliometer, and the principles of operation of these instruments were presented.
4. Methods by which the total radiation intensity on any non-horizontal surface could be obtained from a single reading which included both direct plus diffuse radiation on a horizontal surface were presented and discussed.
5. The above presentation showed that a further study would be essential to determine the intensity of diffuse radiation from various points in the sky for the various conditions of the sky.
6. By means of empirical factors found experimentally by another investigator at Lincoln, Nebraska, a method was presented to find the amount of direct radiation impinging upon any nonhorizontal surface for a clear sky if a horizontal measure of both direct plus diffuse radiation intensities is known.

Measurement of Wind Velocity

To determine the over-all wind velocity at the site of the testing apparatus, a Friez three-cup anemometer, shown in Fig. 7, was mounted on a tower shown in Fig. 7 and 8, the assembly being located about 12 feet east of the test-house with the anememeter 5 1/2 feet above the ridge-roll of the test-house. This particular anemometer has installed within it an integrating odometer dial of the familiar automobile speedometer type which reads to tenths of a mile from zero to 9,999.9 miles, then going back to zero. It also has two sets of terminals so connected that with a recorder or some signalling device electrically attached, the internal mechanisms of the anemometer will cose the circuit instantaneously for either every mile or every 1/60 mile of wind which passes that location.

As used in this study a buzzer bos, Fig. 7 and Fig. 21, mounted on the instrument panel in the control-room of the test-house is commected by wire leads which run through 1/2-inch conduit pipe to the anemometer. The 60th-of-a-mile-terminals are connected in the circuit, so at will an observer may close the switch on the buzzer box and by recording the number of buzzes for a minute there will be obtained directly the velocity of the wind in miles per hour. However, when a 24-hour cycle of readings was taken, the integrating odometer scale was read by climbing the tower, with a flashlight at night, twice

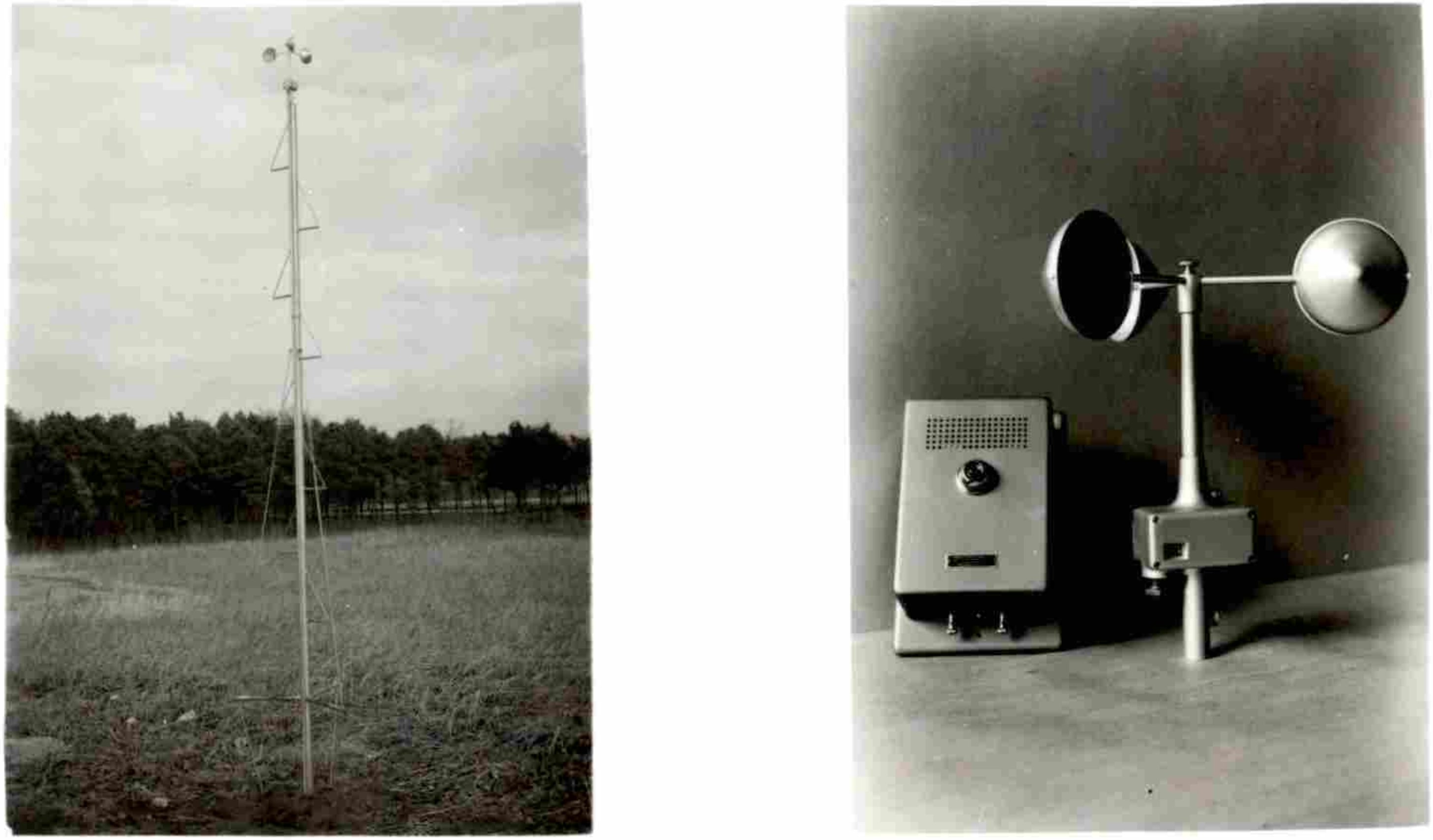
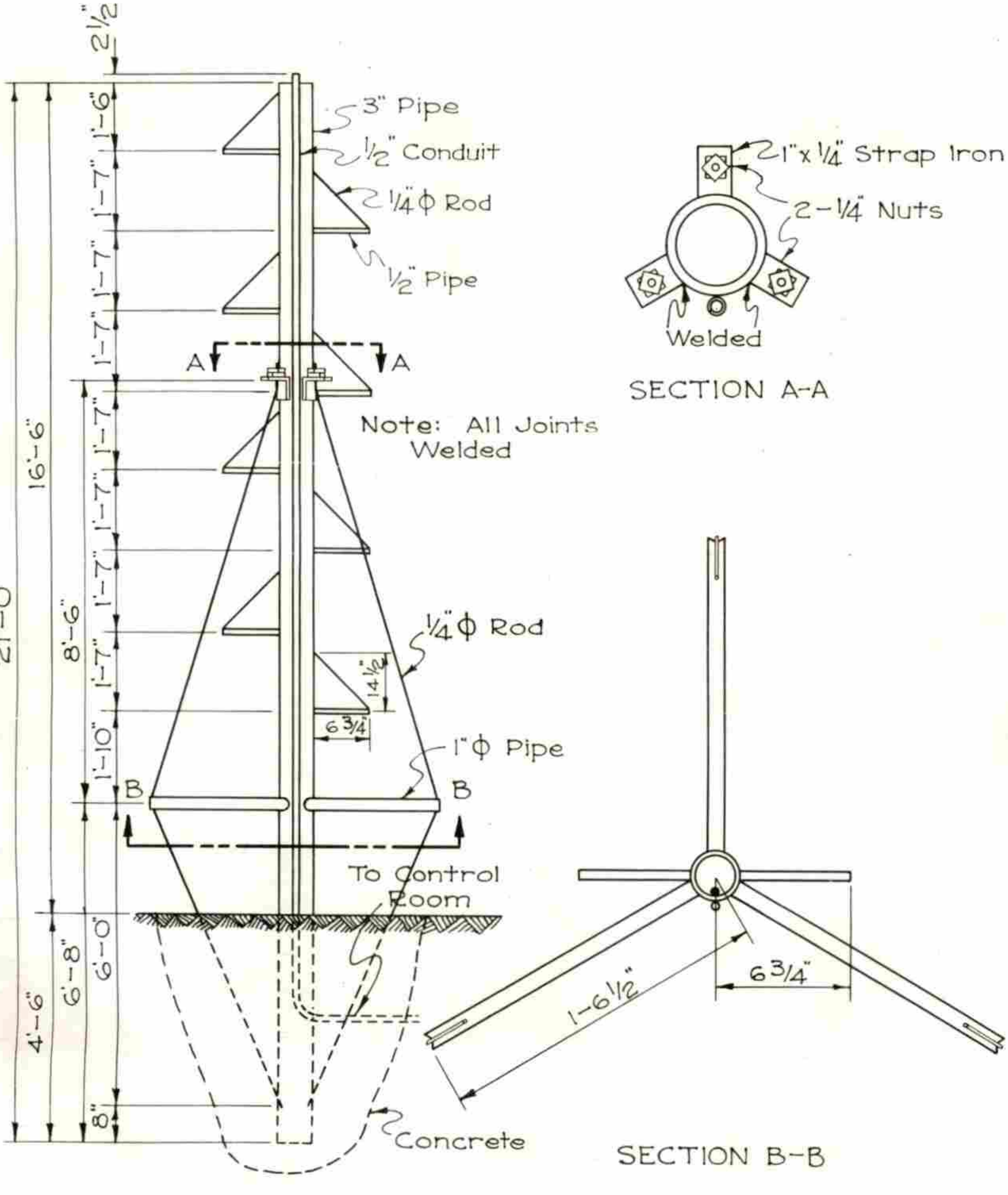


Fig. 7. Three-cup anemometer and tower



CUP ANEMOMETER TOWER

Fig. 8

each hour, 15 minutes after and 15 minutes before the hour. These readings when divided by the time interval gave directly the velocity of the wind in miles per hour. As shown in Fig. 15 these readings were recorded on the data sheets in the column on the right-hand side of the page. Correction tables are unnecessary for the readings obtained with this instrument.

Temperatures Measured Under Sheet Steel Roofing

Testing apparatus

As stated in the section entitled, "Historical," if the reader should desire a more complete description of the construction of the testing apparatus, reference should be made to Mr. Scoates' thesis, "The Effect of Sheet Steel Roofing on Interior Temperatures." However, in continuing the study two more sections have been added, one on each end. See Fig. 9 and 10. The additional feature of the roof sections was the provision of ventilation for the 3 5/8-inch air space enclosed by sheets fastened to each side of the 2" x 4" rafter.

The test-house in its revised form consists of the following ten roof sections:

Type A. 1 1/4" corrugated galvanized sheet steel roofing over 1" x 4" nailing strips 3 feet on centers.

Type B. Wood shingles over 1" x 6" nailing strips 8" on centers.

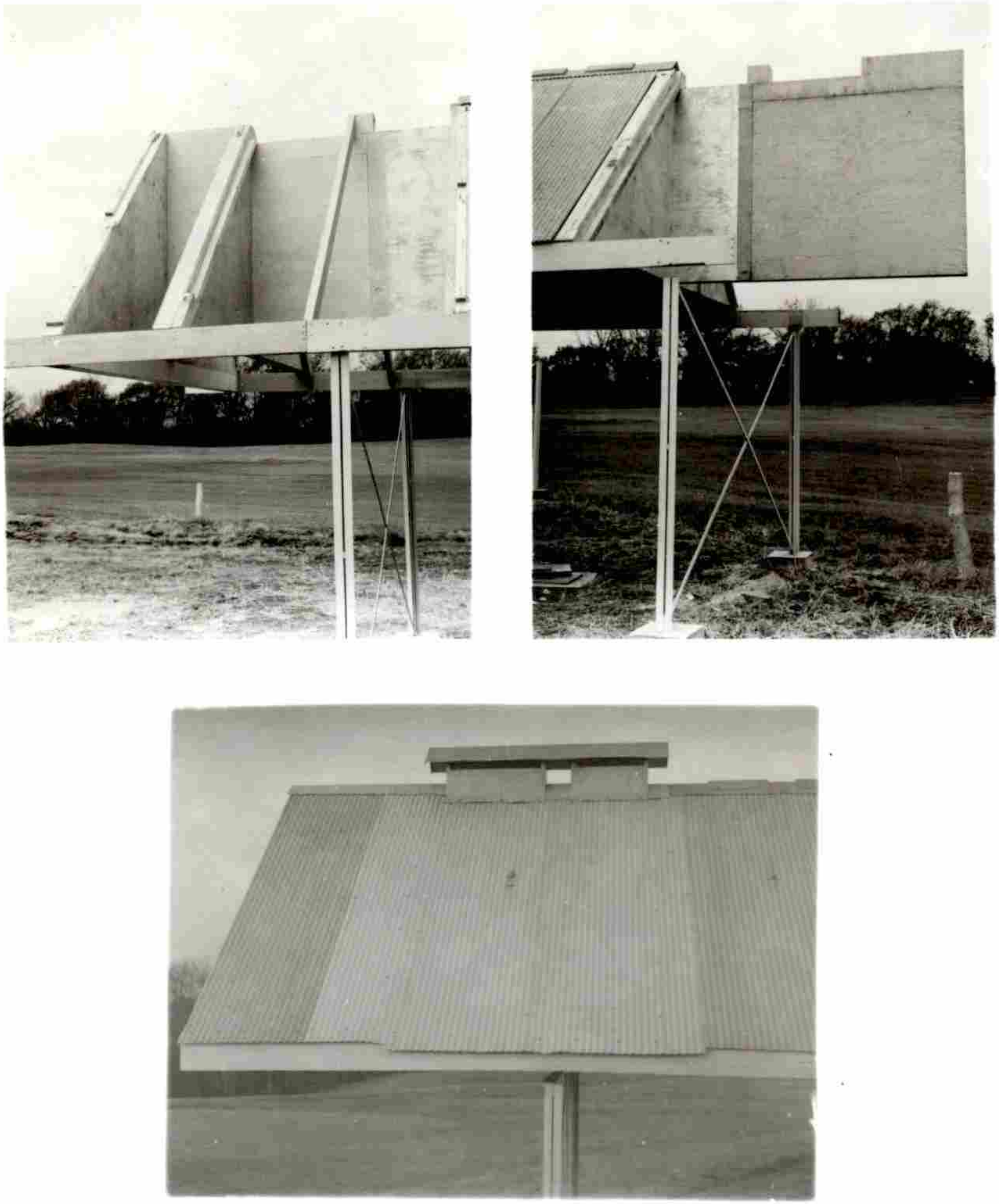


Fig. 9. Construction of additional sections
on each end of test-house

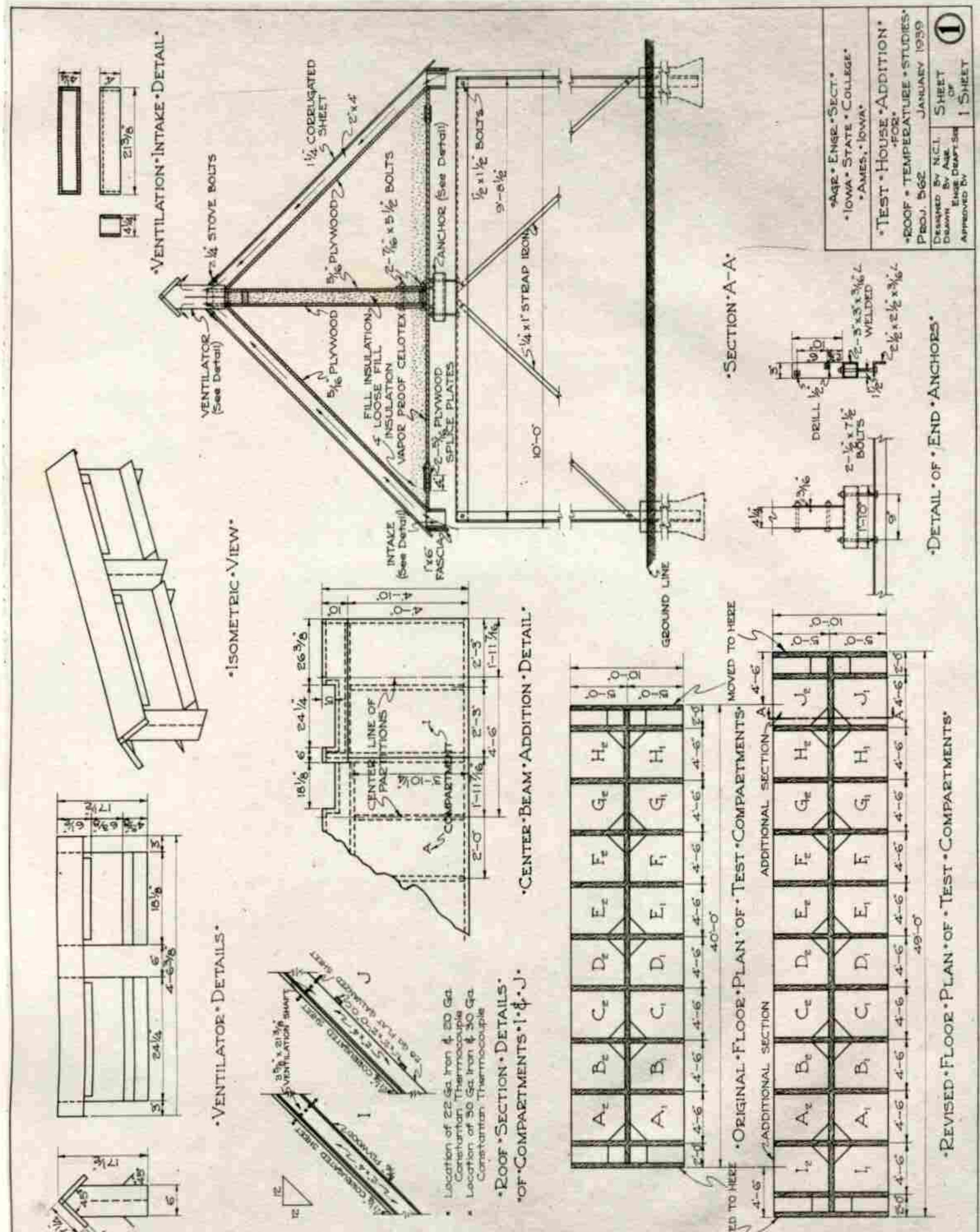


Fig. 10. Revised test-house

Type C. 3 V-crimp galvanized sheet steel roofing over 1" x 4" nailing strip 3 feet on centers.

Type D. 1 1/4" corrugated galvanized sheet steel roofing over 8" shiplap sheathing with sisalkraft paper between sheathing and galvanized sheets.

Type E. 1 1/4" corrugated galvanized sheet steel roofing over 1" structural insulation board.

Type F. 1 1/4" corrugated galvanized sheet steel roofing over 1" x 4" nailing strips 3 feet on centers on the outside with 1" Celotex insulation board on the underside of the rafters.

Type G. 1 1/4" corrugated galvanized sheet steel roofing over 1" x 4" nailing strips 3 feet on centers was placed on the outside. Flat galvanized sheet steel was placed on the underside of the rafters and 1" x 1" stiffener strips were nailed to upper side of the flat galvanized sheets to prevent sagging.

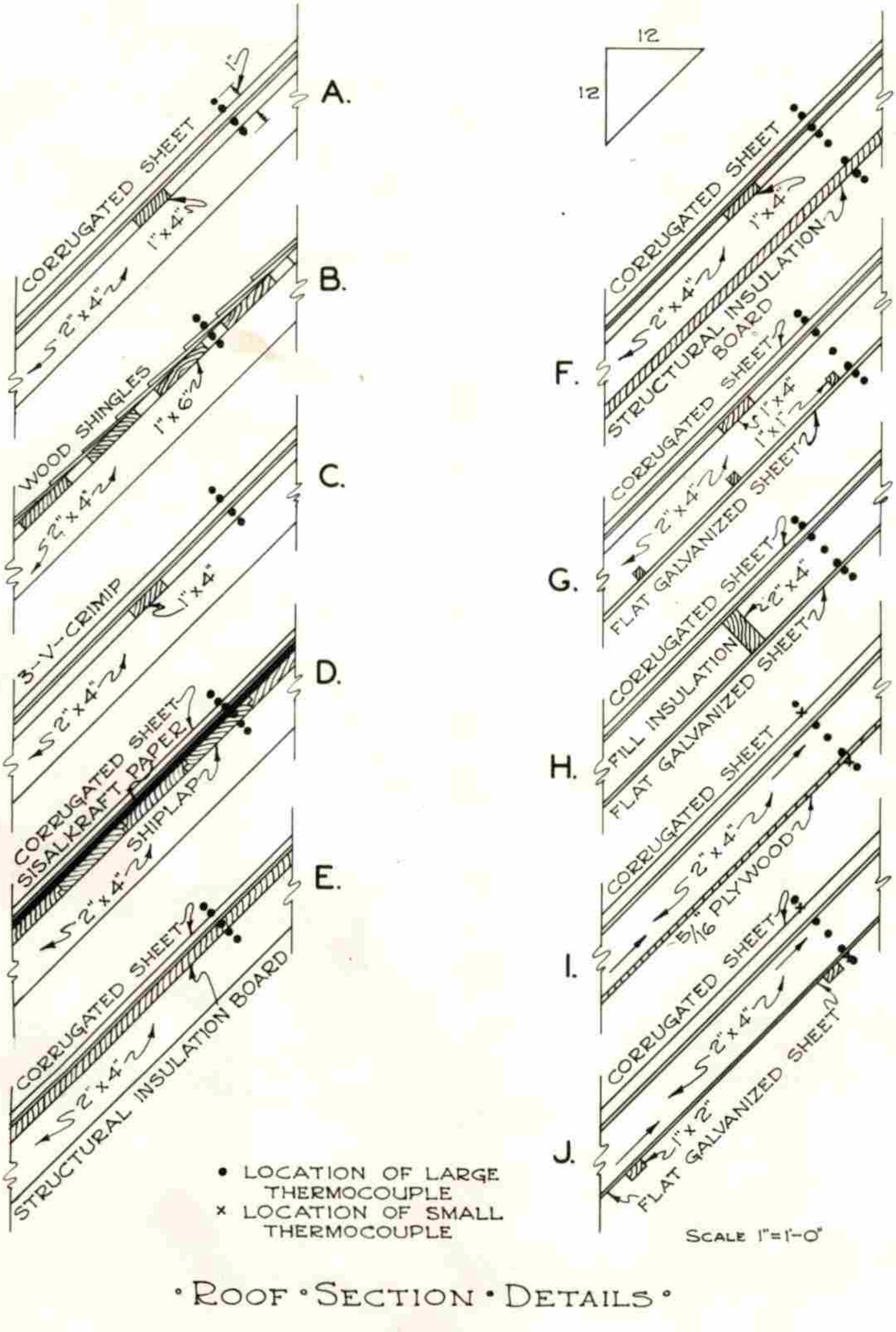
Type H. 1 1/4" corrugated galvanized sheet steel roofing laid over 2" x 4" girts 3 feet on centers. A flat galvanized steel sheet on which were 1" x 1" stiffener strips, was placed on the underside of the rafters. The intervening space was filled with "loose-fill" cornstalk insulation.

Type I. 1 1/4" corrugated galvanized sheet steel roofing nailed directly to the rafters, which were spaced properly to afford nailing at the seams of the sheet steel roofing, with a 5/16" sheet of plywood fastened to the underside of the rafters. Ventilation was provided for the 3 5/8" air space.

Type J. 1 1/4" corrugated galvanized sheet steel roofing nailed directly to the rafters with flat galvanized steel sheets fastened to the underside of the rafters, which were stiffened by 1" x 2" pieces of lumber nailed to the underside of the sheet. Ventilation was provided the 3 5/8" air space.

In the construction of the two additional sections other additional features of construction were incorporated. To provide a more intensive study concerning the effect of different parts of the roof section in retarding the flow of heat, some means of changing the interior of a roof section without molesting the standard roofing material, or corrugated sheet steel, exposed to the exterior should be provided. To provide for this the floor of each additional compartment composed of two pieces of one-inch celotex insulation board spliced together was fastened to the bottom of the four-inch partitions by long screws. The material on the inner side of the rafters is also fastened by screws where possible. The additional sections were constructed according to this method in that, first, the exterior roofing material was fastened in place; second, the interior material of the roof section and the set of thermocouples for the section were installed next; and, finally, the floor was fastened in place. The loose-fill insulation was taken into the compartments half-a-sackful at a time through the manholes. The 10 roof section details are shown in Fig. 11. The original test-house and the test-house in its revised form are shown in Fig. 12 and 13, respectively.

The importance of obtaining accurately the true surface temperature has been emphasized, and there was reason to believe that in the first sets of data this reading was not that of the true surface temperature. The error could have entered from two sources. To describe the first source an understanding of the "Christmas tree" thermocouple wiring arrangement used for each compartment is essential. This



°ROOF °SECTION • DETAILS°

Fig. 11.

Fig. 12. Original test-house with cup anemometer, E. & W. facing

Fig. 13. Revised test-house with electrical installation and cup anemometer tower, N. & S. facing

system consisted of one common constantan lead from which near the end branched out leads to the several iron wires, the two wires being connected at the end to form one junction of the thermocouple. It is easily seen that if any two thermocouples of this wiring system had other electrical contact than through the wires, such as through the galvanized sheet steel, extraneous thermoelectric effects would be established. As originally the case, with two thermocouples of this system fastened on each side of a galvanized sheet there is no evidence which assures no extraneous thermoelectric effects. The second source of error depends upon the position of the thermocouple relative to the surface of the roof section. With No. 18 and 20 B. & S. G. wire thermocouples, the size of all the 120 original thermocouples, placed on top of a sheet steel surface the resulting temperature could be lower than the true surface temperature.

The first error was eliminated in the original sections by placing a thin piece of electrically insulating material on the interior surface of the corrugated sheet steel on which the thermocouple was fastened with Duco household cement. To study the size of wire and the method of fastening the thermocouples to the surface as to their ability in determining the true surface temperature, two No. 18 and 20 B. & S. G. wire thermocouples and two No. 30 B. & S. G. wire thermocouples, one of each pair being soldered and the other of each pair being fastened with Duco household cement were placed on the surface of roof section, type H. Simultaneous readings with temperatures as high as 120 degrees showed that less than a degree difference existed between any two of the four couples. The temperatures were read with a potentiometer. However, the wind velocity was low when these readings were taken and the Duco household cement having been just applied was still fresh. Observations have shown that the sun's rays rapidly destroy the adhesive power of Duco household cement, in that when originally fastened with this cement, the surface thermocouples invariable would become loosened from the roof. This cement for the interior thermocouples has remained in good service. Therefore, to make a more permanent fastener and to assure more nearly accurate surface temperatures the thermocouples were fastened to the surface of the galvanized sheet steel with a thin layer of solder. Solder is a good conductor of heat and it is reasonable to believe that it would approach very closely the temperature of the material directly adjacent to it. When constructing the new sections, two small wire thermocouples, No. 30 B. & S. G., were used for the outside and inside surface thermocouples, the other thermocouples being the same size as those originally used. Since the constantan and iron wires for each of these couples ran all the way to the instrument panel, all extraneous thermoelectric effects were eliminated. With the junction of these small wires being soldered to the outside surface the true surface temperature would be measured with a high degree of accuracy.

The use of these smaller wires with their greater resistance to flow of electricity made the temperature readings with the galvanometer calibrated for the original 120 thermocouples lower than that of the true temperature. Also, since the large-wire thermocouples were longer by 4 feet 6 inches than those of the original sections, more resistance would be inserted in the galvanometer circuit, making these readings lower than the true temperature. Calibrating both the large and small size wire thermocouples for the additional two pairs of sections over a temperature range from 40 to 200° F. showed that the small amount of extra resistance added to the circuit by the 4 feet 6 inches of large size wire was negligible in its effect on the true reading. However, it was necessary to plot a calibration curve for the small wire couples from which the true temperatures were always read before they were recorded on the data sheets. This permitted all the temperature readings to be made with the galvanometer calibrated as it was for the 120 original couples.

The ridge-roll ventilators and intakes were built from flat galvanized sheet steel and plywood, respectively. The details of construction are shown in Fig. 10. The two additional roof sections have been exposed to winter conditions only, since their construction was not completed until January, 1939.

Since the method of measuring relative humidity by exposing two thermocouples to the outside air, one of which was covered with a dampened wick extending from a small vessel of water, was found to be inaccurate and since at the present time relative humidity is felt to have little effect upon heat flow through roof sections, this measurement was discontinued.

The wiring diagram for the thermocouple circuit is the result of considerable effort to achieve a thermocouple wiring system free from all thermoelectric and electrolytic effects which make for errors in the temperature readings. The galvanometer, purchased especially for this work, is a very sensitive instrument having only 12.3 ohms internal resistance, and a sensitivity of 0.34 microvolts per mm. The reason for such a sensitive instrument is to provide for a combination of the damping and period of first swing which makes the time for the coil to come to rest for any given reading a minimum. With this galvanometer an experienced operator has read and recorded 156 temperatures in 20 minutes, or a reading made and recorded every 7 1/2 seconds. The two principles which were discovered as essential for a sound thermocouple wiring circuit are: (1) to have all dissimilar metal wire junctions at places of positively equal temperatures; (2) to eliminate all electrolytic effects if an ice-water mixture is used for the cold junction. The first feature was incorporated as shown in the wiring diagram shown in Fig. 14 by using the series and shunt resistances having their junctions within the Thermos bottle. These resistances consisted of manganin wire wrapped on a piece of heavy cardboard. Manganin has a low temperature coefficient of resistance. Electrolytic effects were nullified by placing the leads to be immersed in the ice-water in small glass tubes which were partially filled with mercury to provide for good thermal conductance of the ice-water to the terminals. Mercury does not freeze when exposed to temperatures of Iowa winter weather. The three glass tubes were inserted in a rubber stopper, making it convenient to remove and replace the tubes in the ice bottle. When readings with the pyranometer were desired, the two-way switch shown in Fig. 14 enabled the galvanometer to be conveniently taken from the thermocouple to the pyranometer circuit or vice versa.

With the addition of a section on each end it was necessary to devise a new means of anchoring the test-house. The detailed plans for the revised method of anchoring the test-house are shown in Fig. 10. It will be noted that these anchors were designed for only upward and horizontal forces. The central cylindrical support carries all the static load, while the end anchors stabilize the structure for high wind velocities and hold it in a given position of orientation.

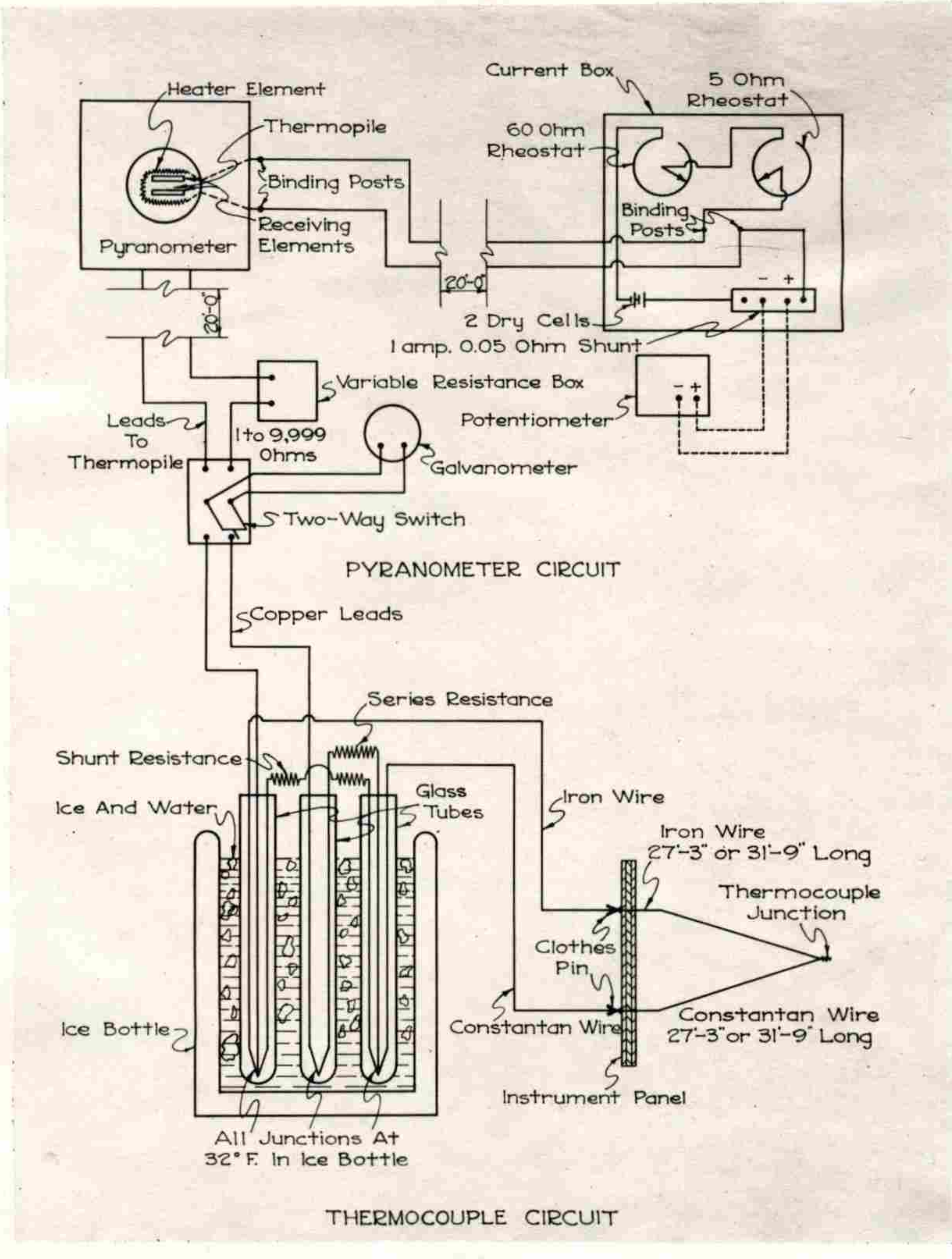


Fig. 14. Wiring diagram for thermocouple and pyranometer circuit

<u>Method of procedure</u>

To show the kinds of information desired, a set of readings covering at least a 24-hour cycle was necessary. As different equipment was added during the study a few minor changes were necessary in the testing procedure, but the fundamental procedure which was followed gave the following observations as recorded on data sheets, Fig. 15, Table IX gives the meaning of the symbols used for these data sheets:

1. A set of temperature readings for all the roof sections for each hour of the day. Since it took approximately 20 minutes to read a complete set of temperature readings, the time for beginning the set would be about 10 minutes before the hour with the time of completion being 10 minutes after the hour, making the average time, the time used for all the readings in analyzing the data, fall on the even hour. The outside air temperature was read before and after each set of readings.
2. The odometer dial of the cup anemometer was read and recorded 15 minutes before and 15 minutes after each hour. Multiplying the difference of these readings by two gave the average velocity of the wind in miles per hour for increments of a half-hour.
3. The date, time and observer were labelled on each sheet,

ROOF TEMPERATURES

DATE 8-4-38 OPERATOR Ives

START TIME 4:53 A. M. FINISH TIME 5:09 A. M.

T_D 61.0 T_W - R.H. - % T_D 61.0 T_W - R.H. - %

COMPARTMENT	T_o	T_{os}	T_1	T_2	T_3	T_{is}	T_i	R_1	R_2	AIR VELOCITY AT T_o
A_{1n}	59.0	56.5				59.0	63.0	64.5	63.5	225 fpm.
B_{1n}	59.5	57.0				62.0	64.5	65.0	65.0	225 "
C_{1n}	59.5	55.0				60.0	63.5	64.0	64.0	225 "
D_{1n}	59.5	58.5	60.0	61.5		65.5	66.5	67.5	67.0	225 "
E_{1n}	60.5	58.0	60.0			67.5	67.5	69.0	68.5	225 "
F_{1n}	59.5	57.5	58.0	60.0	62.0	65.5	66.0	66.5	66.0	225 "
G_{1n}	59.5	57.5	57.5	60.5	62.5	62.5	65.0	65.5	65.0	225 "
H_{1n}	59.0	57.5	57.0	62.5	66.5	67.0	68.0	67.5	68.0	77 "
WIND	Direction: North Velocity : 2.2 mph.					Sky: Partly cloudy				
A_{2s}	59.5	59.0				60.5	65.0	65.0	66.0	192 fpm.
B_{2s}	60.0	58.0				63.0	66.0	66.0	66.0	192 "
C_{2s}	59.5	60.0				60.5	64.5	64.5	64.5	192 "
D_{2s}	59.5	60.0	61.5	62.5		65.5	67.5	67.5	67.5	192 "
E_{2s}	60.0	60.0	60.5			67.0	67.5	67.5	67.5	192 "
F_{2s}	60.0	59.0	59.5	61.0	63.5	66.0	66.5	67.5	67.5	192 "
G_{2s}	59.0	59.0	59.5	61.0	62.5	64.0	65.0	66.0	65.5	192 "
H_{2s}	60.0	59.0	59.5	65.0	67.5	67.5	68.0	69.0	68.5	192 "

ROOF TEMPERATURES

DATE 1-19-39 OPERATOR Rollins

START TIME 1:45 P. M. FINISH TIME 2:14 P. M.

T_D 29.0 T_W - R.H. - % T_D 30.5 T_W - R.H. - %

COMPARTMENT	T_o	T_{os}	T_1	T_2	T_3	T_{is}	T_i	R_1	R_2	AIR VELOCITY AT T_o
A_{1n} I_{1n}	29.0	38.5	40.0	43.5	49.5	57.0	32.0	61.5	61.5	
A_{1n}	28.0	42.5				46.0	61.5	65.0	65.5	
B_{1n}	28.0	40.5				58.5	65.0	66.0	68.0	Time 1:45 P.M.
C_{1n}	28.0	42.5				43.5	61.5	65.5	63.5	Reading 6922.6
D_{1n}	27.0	39.5	40.0	42.0		61.5	66.0	68.5	68.5	Velocity 4.8 mph.
E_{1n}	26.5	33.0	42.5			74.5	76.5	79.5	80.5	
F_{1n}	26.5	35.0	37.5	47.5	55.0	85.0	89.5	91.5	90.5	
G_{1n}	30.5	30.5	34.5	54.0	67.0	67.5	78.0	83.0	81.0	
H_{1n}	27.0	28.5	29.5	53.0	86.5	87.0	91.5	92.5	93.0	
H_{1n} F_{1n}	26.5	33.0	34.0	44.5	54.5	55.0	64.5	65.0	66.0	
WIND	Direction: SW Velocity : 0.6 mph.			Sky: Clear Radiation intensity: 0.53 g. cal. min.$^{-1}$cm.$^{-2}$						
A_{2s} I_{1s}	40.5	107.0	101.0	66.0	70.5	72.0	76.0	75.5	74.5	
A_{2s}	36.5	107.0				109.5	104.0	97.5	95.5	
B_{2s}	42.5	118.0				90.0	88.5	89.0	91.0	Time 2:15 P.M.
C_{2s}	46.5	119.5				124.0	121.0	114.0	112.0	Reading 6924.7
D_{2s}	41.5	120.5	120.5	116.0	-	106.5	103.0	102.5	103.0	Velocity 4.2 mph.
E_{2s}	39.0	123.0	123.0			105.5	101.5	98.0	97.5	
F_{2s}	40.0	107.5	109.5	93.5	94.0	99.0	99.5	101.0	99.0	
G_{2s}	38.0	121.5	119.5	97.0	101.5	99.0	101.5	102.0	99.5	
H_{2s}	42.0	126.0	127.5	100.0	100.5	101.5	101.0	101.0	100.5	
H_{2s} F_{1s}	39.0	104.0	96.5	48.0	67.0	71.5	78.5	80.5	77.5	

ROOF TEMPERATURES

DATE 1-27-38 OPERATOR Ives

START TIME 1:40 P. M. FINISH TIME 2:03 P. M.

T_D 37.5 T_W - R.H. - % T_D 2.30 T_W - R.H. - %

COMPARTMENT	T_o	T_{os}	T_1	T_2	T_3	T_{is}	T_i	R_1	R_2	AIR VELOCITY AT T_o
A_{1n} I_{1n}	39.5	43.5	44.0	44.5	47.5	57.0	63.0	60.5	59.0	
A_{1n}	39.5	46.0				51.0	62.5	64.5	66.5	
B_{1n}	41.0	49.0				66.0	67.5	69.5	72.0	Velocity 20 mph.
C_{1n}	40.0	43.0				53.5	67.0	71.5	71.5	
D_{1n}	39.5	47.0	50.0	54.5		67.0	71.0	73.5	74.0	
E_{1n}	40.0	46.0	55.5			82.0	84.0	85.0	85.0	
F_{1n}	39.0	45.5	49.0	59.0	66.0	87.5	89.5	89.5	88.5	
G_{1n}	41.0	45.5	47.5	64.5	74.0	76.5	82.0	82.0	81.0	
H_{1n}	39.0	43.5	45.5	67.0	91.0	91.5	92.5	93.5	93.0	
H_{1n} F_{1n}	40.0	43.0	44.0	44.0	55.5	55.0	66.5	69.0	69.5	
WIND	Direction: SE Velocity : 20 mph.			Sky: Partly Cloudy Radiation intensity: 0.662 g.cal.min.$^{-1}$cm.$^{-2}$						
A_{2s} I_{1s}	44.5	64.0	77.0	59.0	64.0	68.5	70.5	71.5	71.0	
A_{2s}	43.5	76.0				80.5	75.5	72.5	74.5	
B_{2s}	45.0	63.5				71.5	72.0	73.5	76.0	Velocity 20 mph.
C_{2s}	47.0	85.5				92.0	97.0	93.0	94.5	
D_{2s}	46.5	85.5	85.0	82.0		83.0	83.0	83.0	84.5	
E_{2s}	43.5	80.0	84.0			88.0	85.5	85.0	81.0	
F_{2s}	44.0	73.5	74.0	61.5	67.5	86.5	92.0	86.0	83.0	
G_{2s}	44.0	76.0	77.0	67.0	76.0	74.5	82.0	78.0	78.0	
H_{2s}	44.0	73.0	80.0	77.5	80.5	86.5	86.5	87.5	88.0	
H_{2s} F_{1s}	43.5	63.0	69.5	58.0	68.0	69.0	80.5	84.0	82.5	

ROOF TEMPERATURES

DATE 2-3-39 OPERATOR Ives

START TIME 4:35 P. M. FINISH TIME 4:55 P. M.

T_D 22.5 T_W - R.H. - % T_D 23.0 T_W - R.H. - %

COMPARTMENT	T_o	T_{os}	T_1	T_2	T_3	T_{is}	T_i	R_1	R_2	AIR VELOCITY AT T_o
A_{1n} I_{1n}	20.0	23.0	25.0	29.5	44.5	55.0	67.0	64.5	63.0	
A_{1n}	19.5	32.5				46.0	53.0	58.0	56.0	
B_{1n}	20.0	30.0				33.5	63.5	64.0	65.0	Time 4:10 P.M.
C_{1n}	20.0	34.0				52.0	68.5	64.0	64.0	Reading 137.4
D_{1n}	19.0	29.0	33.0	39.5		58.5	64.5	68.0	68.5	
E_{1n}	19.5	22.5	33.5			72.0	74.0	76.0	76.5	
F_{1n}	20.0	22.5	26.5	36.5	48.0	86.0	92.0	92.0	91.0	
G_{1n}	20.0	24.0	27.0	41.5	59.0	60.0	72.0	77.5	75.5	
H_{1n}	19.0	20.5	21.5	47.0	89.0	87.5	94.0	95.5	95.0	
H_{1n} F_{1n}	19.0	22.0	23.5	27.0	47.5	50.0	65.0	67.5	67.0	
WIND	Direction: - Velocity : 0.6 mph.			Sky: Clear Radiation intensity: 0.116 g.cal.min.$^{-1}$cm.$^{-2}$						
A_{2s} I_{1s}	24.0	26.0	32.5	30.5	51.0	61.0	72.0	71.0	69.0	
A_{2s}	30.0	60.0				66.5	77.5	81.5	82.5	
B_{2s}	31.0	63.5				94.0	103.0	104.5	105.5	Time 5:00 P.M.
C_{2s}	32.0	69.5				74.5	95.0	101.0	101.5	Reading 138.0
D_{2s}	31.0	67.5	69.0	76.0		93.5	99.5	100.5	101.5	
E_{2s}	30.5	60.5	69.0			106.5	107.0	107.5	107.0	
F_{2s}	27.0	51.0	58.0	56.5	82.0	110.5	117.5	114.0	109.0	
G_{2s}	25.0	52.5	57.5	66.0	88.0	91.5	105.0	102.5	98.0	
H_{2s}	22.5	46.0	53.5	101.5	120.5	121.0	122.0	122.5	121.0	
H_{2s} F_{1s}	20.0	23.0	27.5	27.5	49.0	52.0	71.0	74.5	71.0	

Fig. 15. Temperature data sheets

Omit

Table IX. Legend of Symbols

T_d	Outside air temperature
T_0	Outside temperature one inch above roof
T_{oa}	Outside surface temperature of roofing
T_1	Temperature within roof section
T_2	Temperature within roof section
T_3	Temperature within roof section
T_{is}	Inside surface temperature of roof section
T_i	Inside temperature one inch below roof section
R_1	Compartment temperature twelve inches below roof section
R_2	Compartment temperature twenty-four inches below roof section
A_1	Compartment A on right-hand side of the house
A_2	Compartment A on left-hand side of the house
A_{1W}	Compartment A_1 facing west direction
A_{1N}	Compartment A_1 facing north direction
A_{2E}	Compartment A_2 facing east direction
A_{2S}	Compartment A_2 facing south direction

to identify it adequately if lost from the rest of the data.

Twenty- four such sets of data, one for every hour of the day comprised a day's set of temperature readings. On another sheet for each day's set of data the condition of the sky as to cloudiness, the wind direction and the observer's idea of its velocity, and other general remarks of weather conditions were observed and recorded for each hour.

Such sets of data have been obtained for the following dates: 6-18-38, 6-19-38, 6-22-38, 6-23-38, 6-25-38, 7-6-38, 7-7-38, 7-8-38, 7-12-38, 7-29-38, 8-2-38, 8-3-38, 8-4-38, 8-13-38, 9-24-38, 10-4-38, 10-11-38, 10-14-38, 1-12-39, 1-19-39 (with artificial heat in compartments).

As described in Mr. Scoates' theses the test-house was constructed so it could be oriented with the roof surfaces facing either north and south or east and west to study the effect of orientation as a factor affecting the amount of heat entering a roof section, and ventilators were built into all of the compartments to study the effect of ventilation in its ability to remove accumulated heat from solar radiation in the summer. It is seen, therefore, that there are four possible arrangements of the test-house, namely:

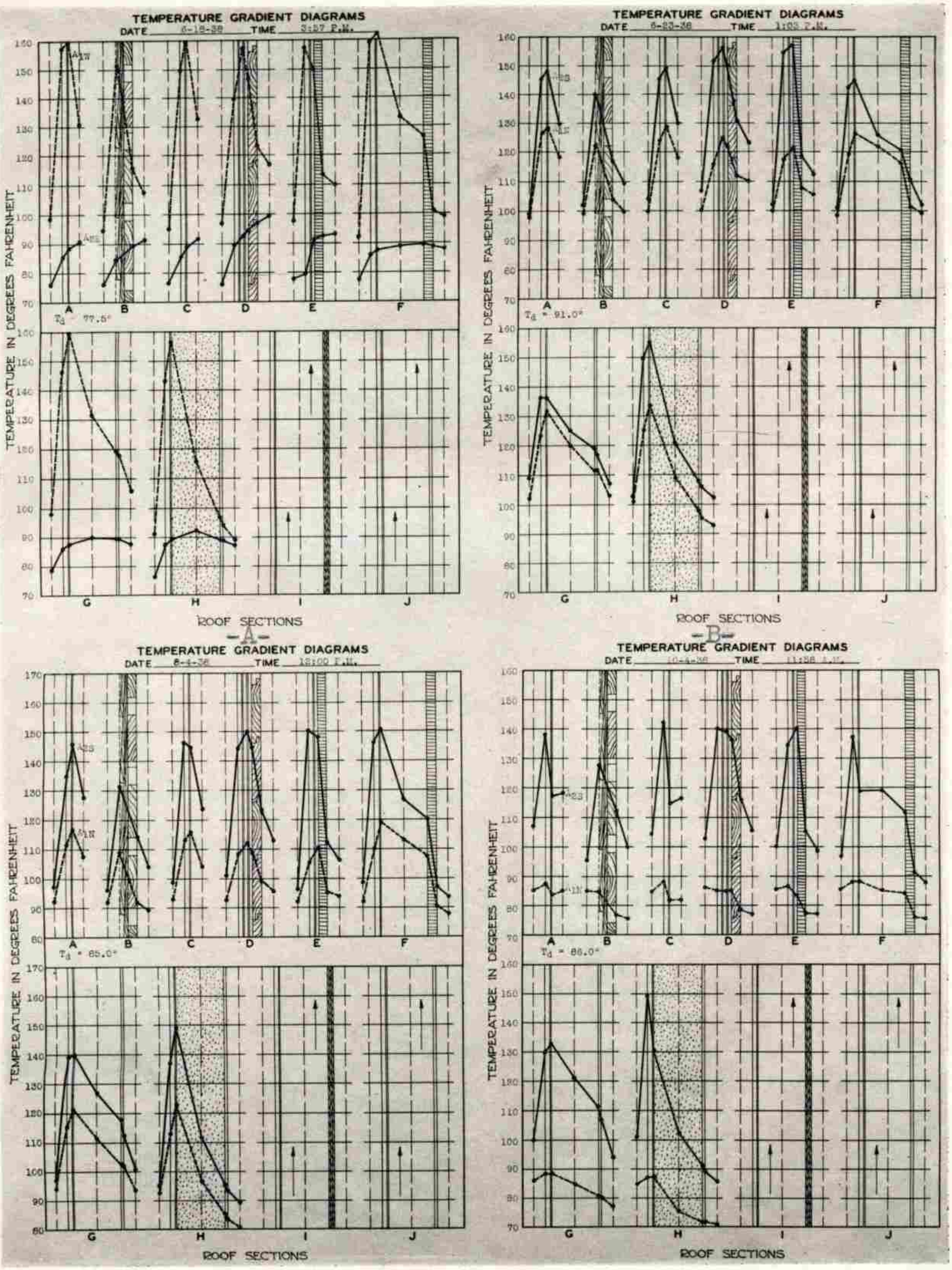
1. E & W orientation, which makes for a north and south exposure, with the ventilators closed
2. E & W orientation, ventilators open
3. N & S orientation, ventilators closed

4. N & S orientation, ventilators open

Results

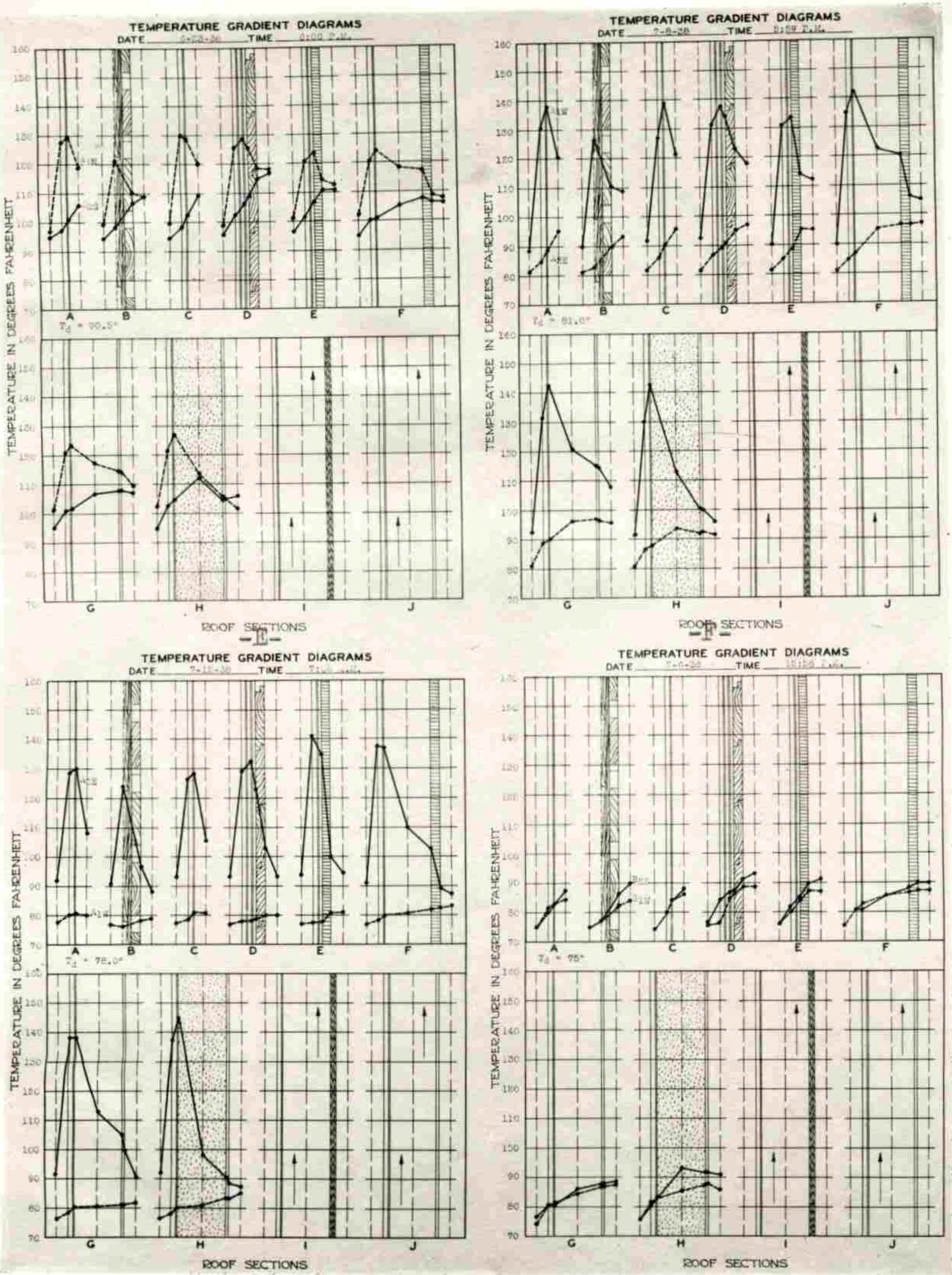
To study and compare the results of these data for all the different conditions under which they were obtained demands certain criteria by which the different influential factors may be compared. Representative data have been plotted or shown in the following forms to offer a means for comparing the different sections for the different conditions:

1. Temperature gradient diagrams, Fig. 16. These diagrams show the temperatures at all points in the test-house for a given set of environmental conditions. Therefore, they are directly comparable for the one set of conditions under which they were obtained.
2. Compartment temperature diagrams, Fig. 17. These diagrams when plotted for each section for a given day show the relative temperatures of all the roof section compartments and since it can be considered, for all practical purposes, that the specific heat of all the compartments is the same, the temperatures indicate directly the relative amounts of heat contained by each compartment. Likewise, the temperature difference between any two compartments indicates directly the relative amounts of heat which have been transmitted under identical environmental conditions by these two roof sections.



-C- -D-

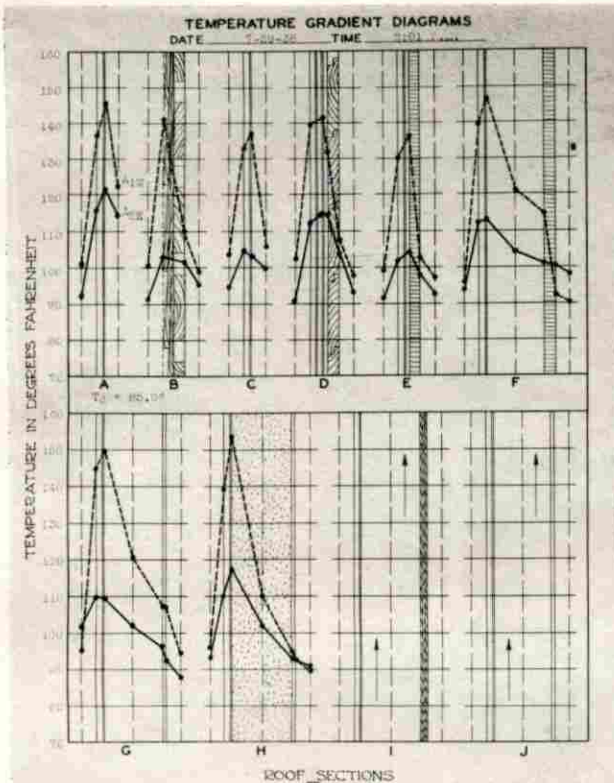
Fig. 16. Temperature gradient diagrams



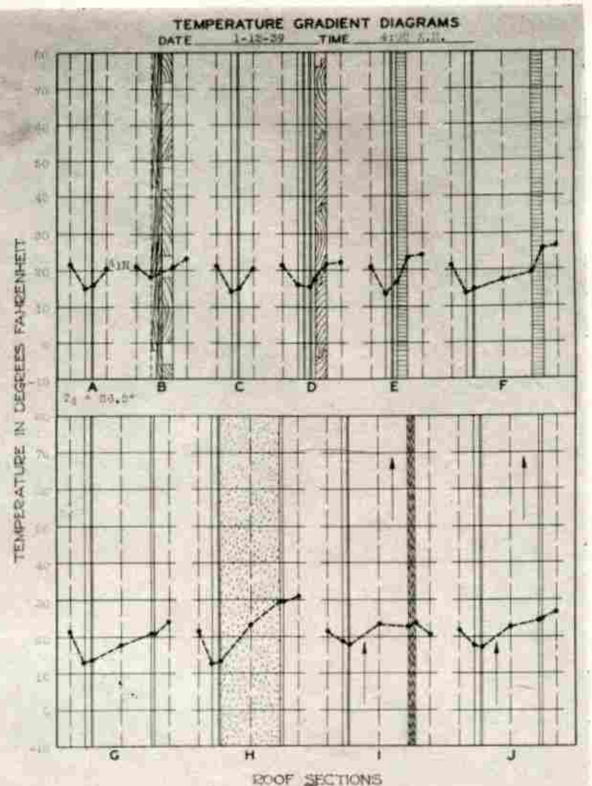
-G-

-H-

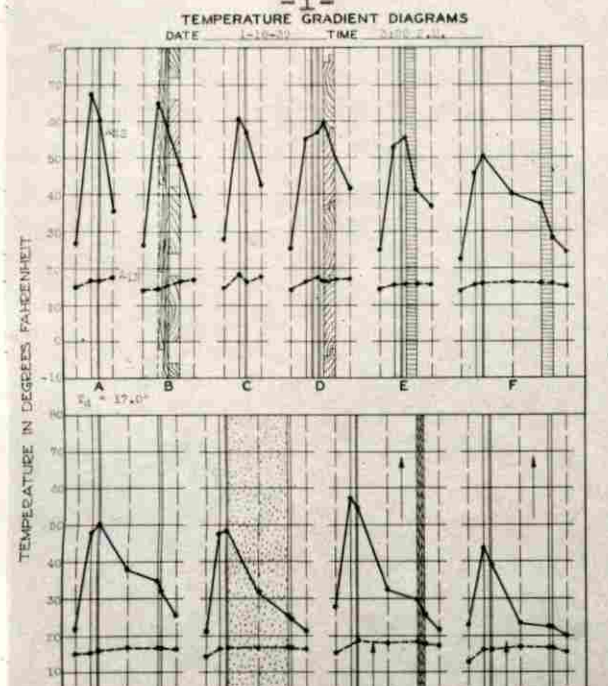
Fig. 16. (Cont.)



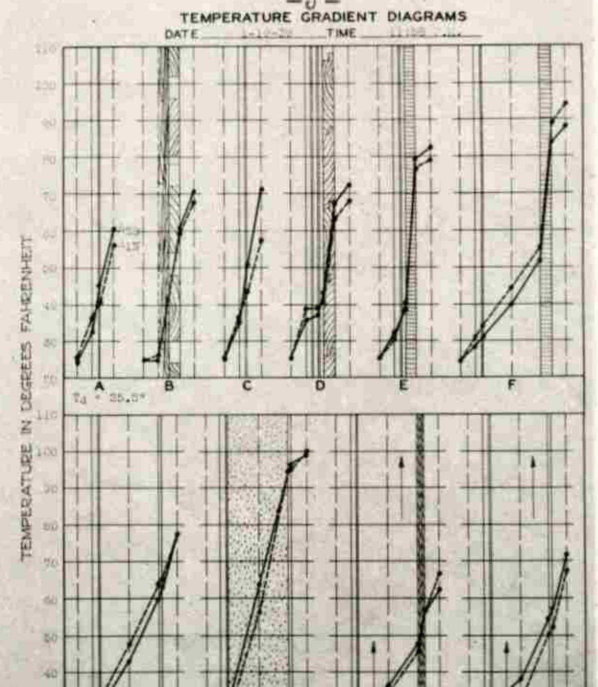
-I-



-J-



-K-



-L-

Fig. 16. (Cont.)

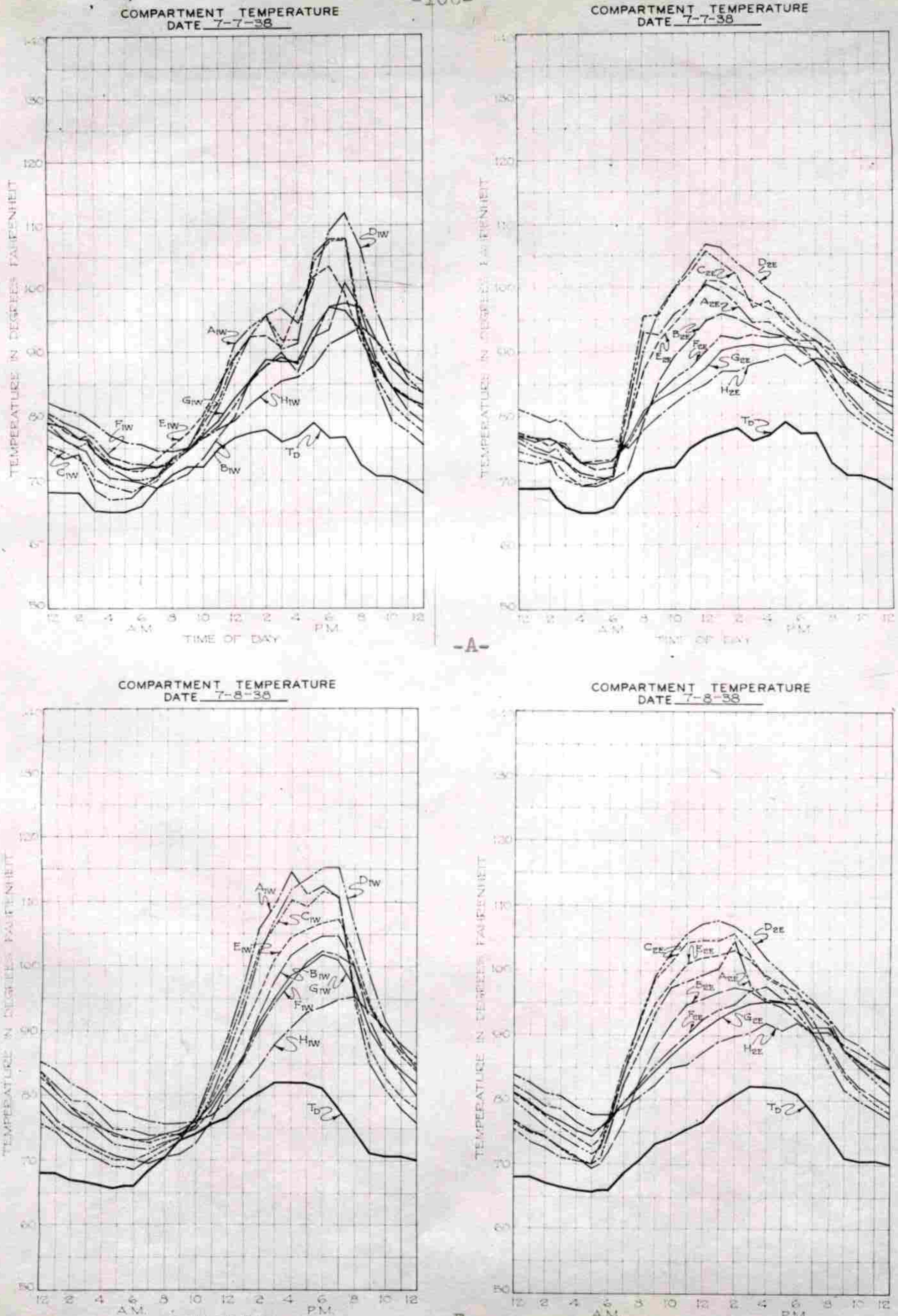
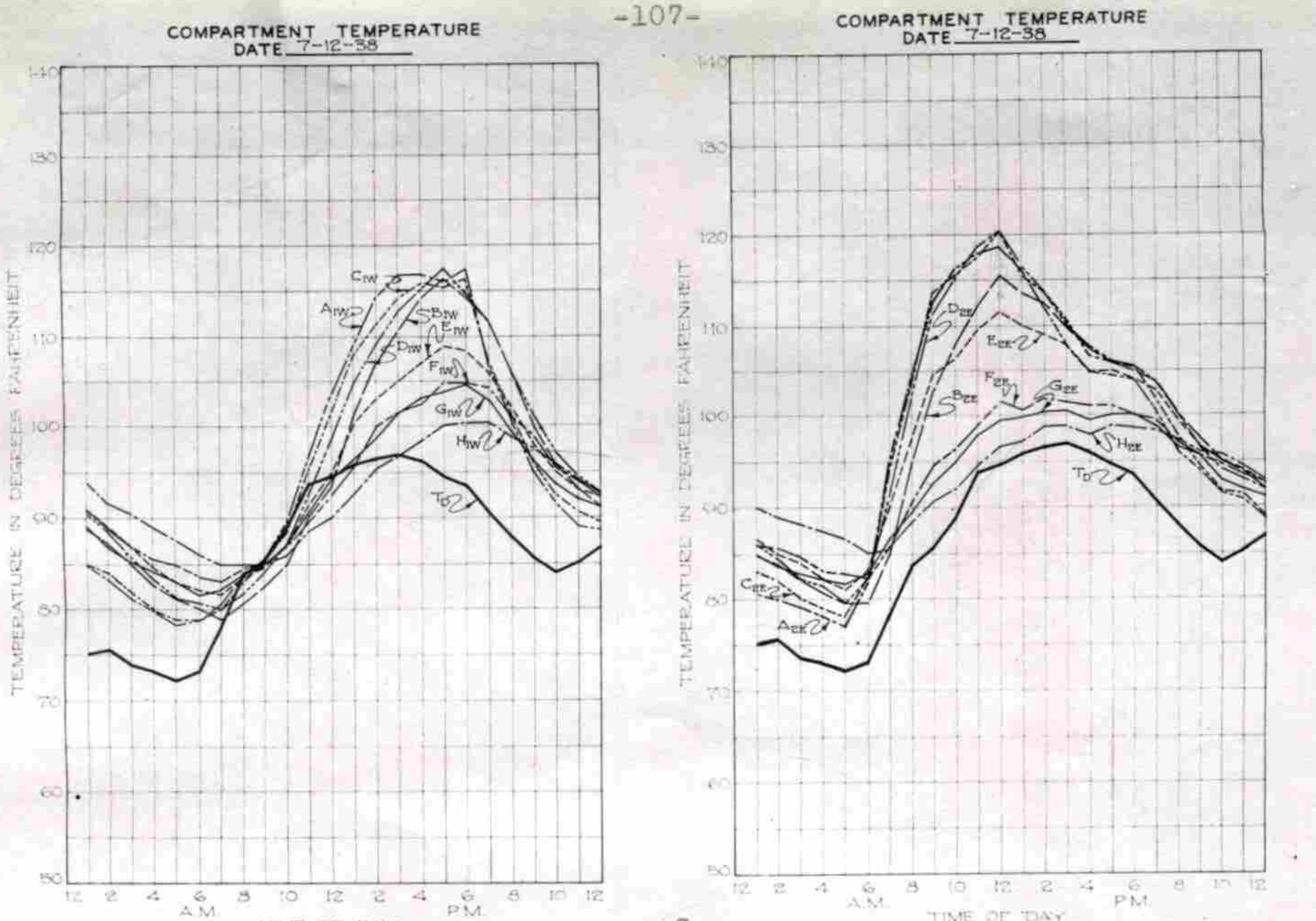
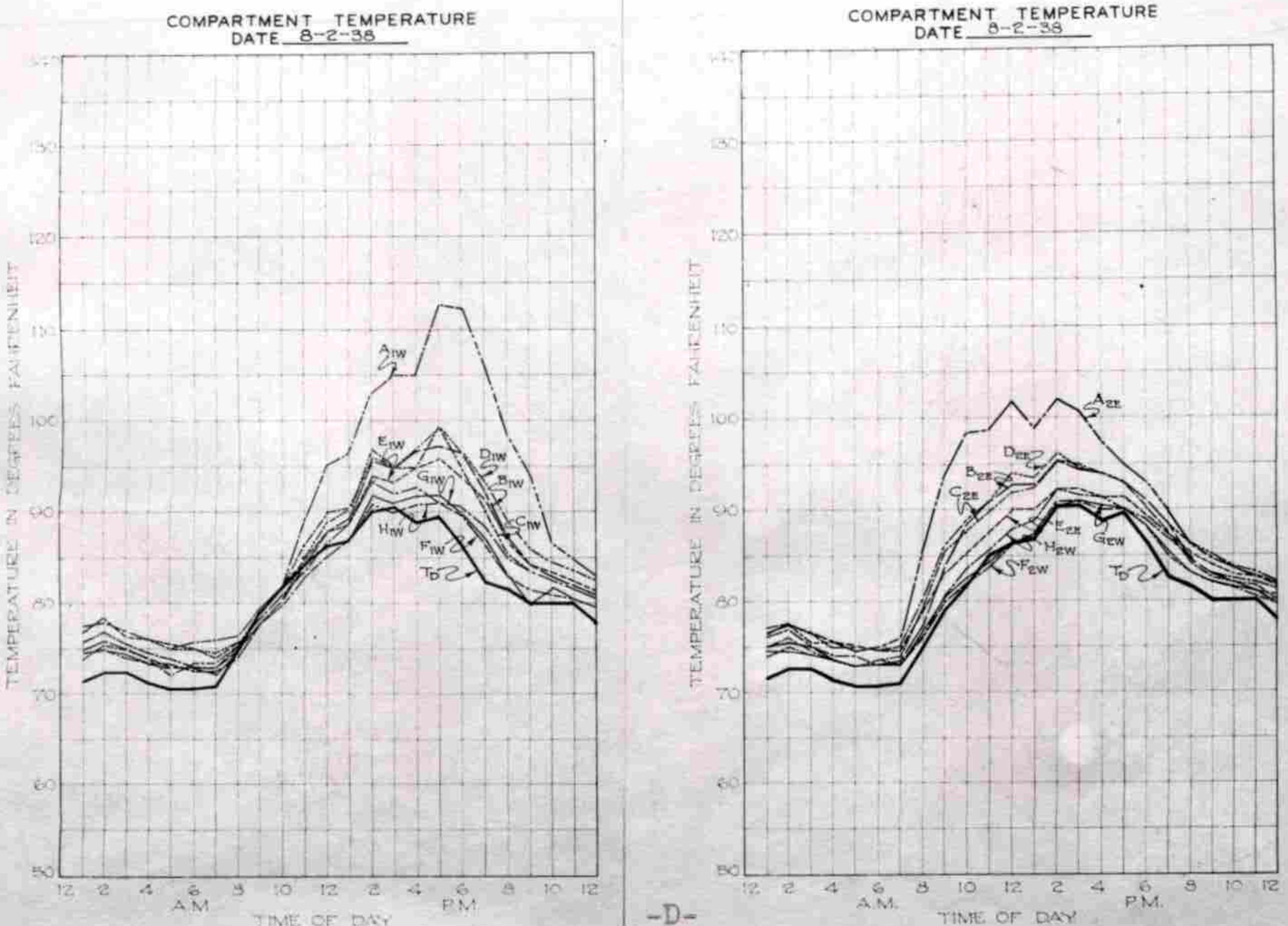


Fig. 17. Compartment temperature diagrams.



-C-



-D-

Fig. 17. (Cont.)

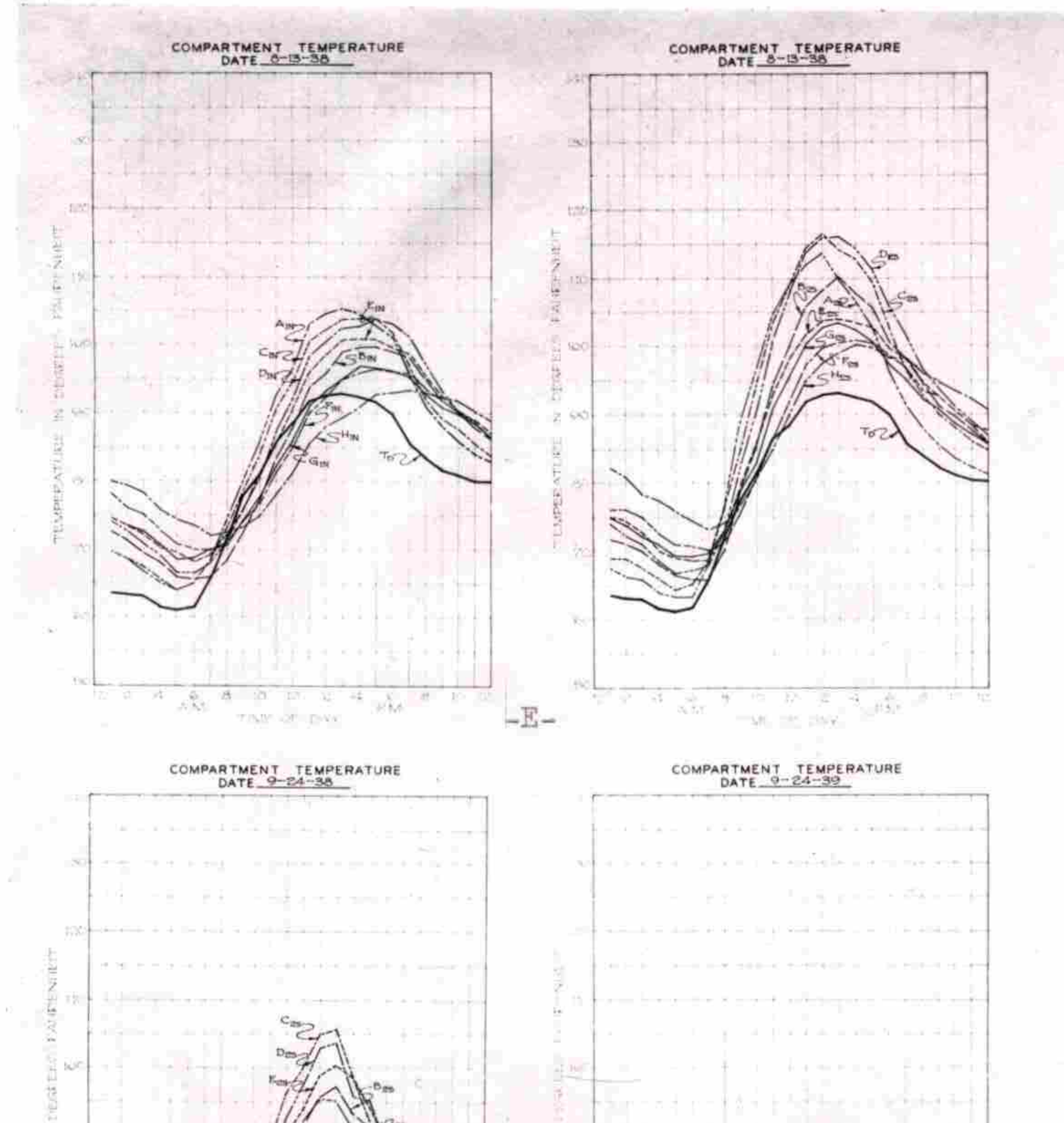
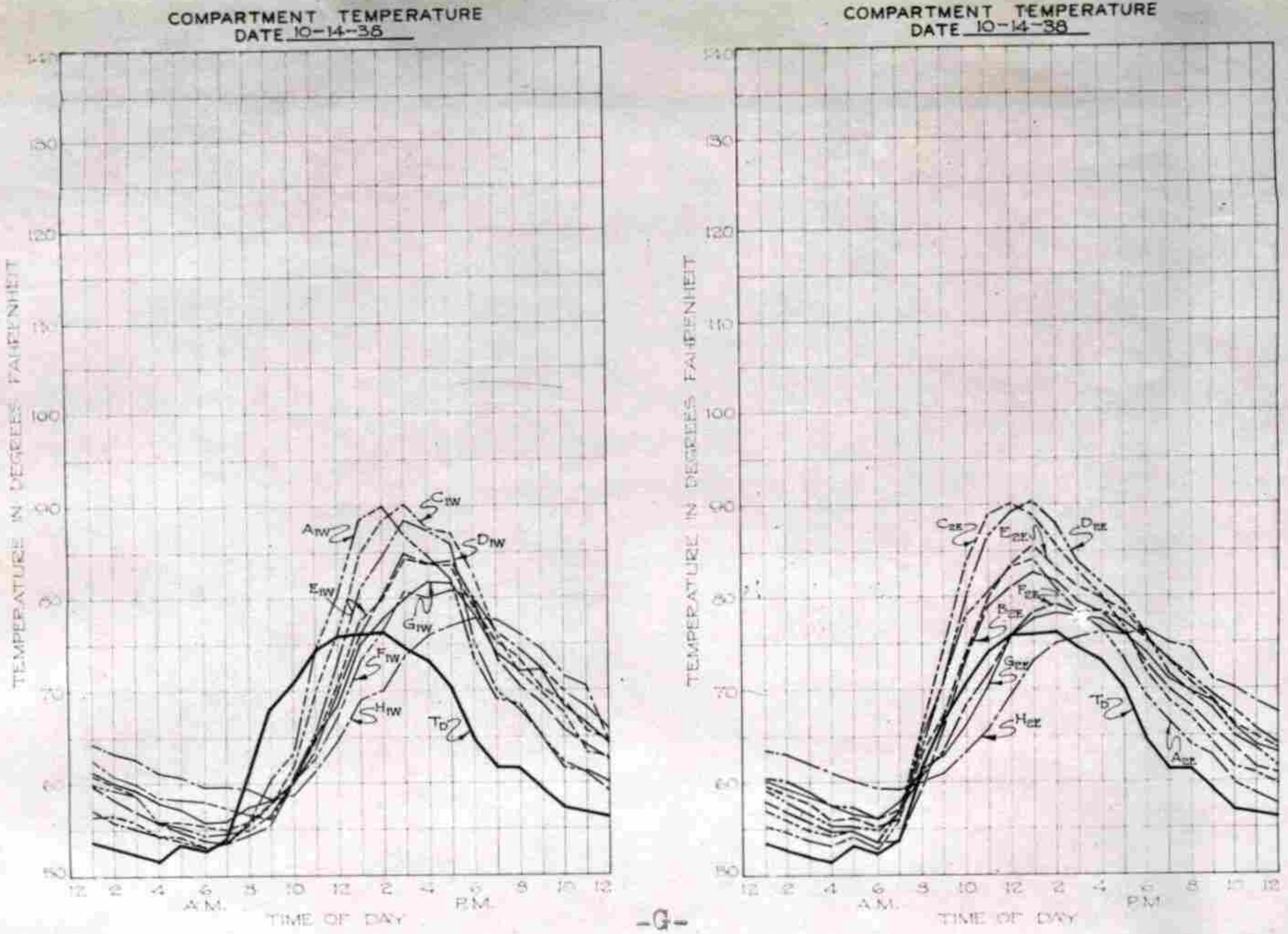
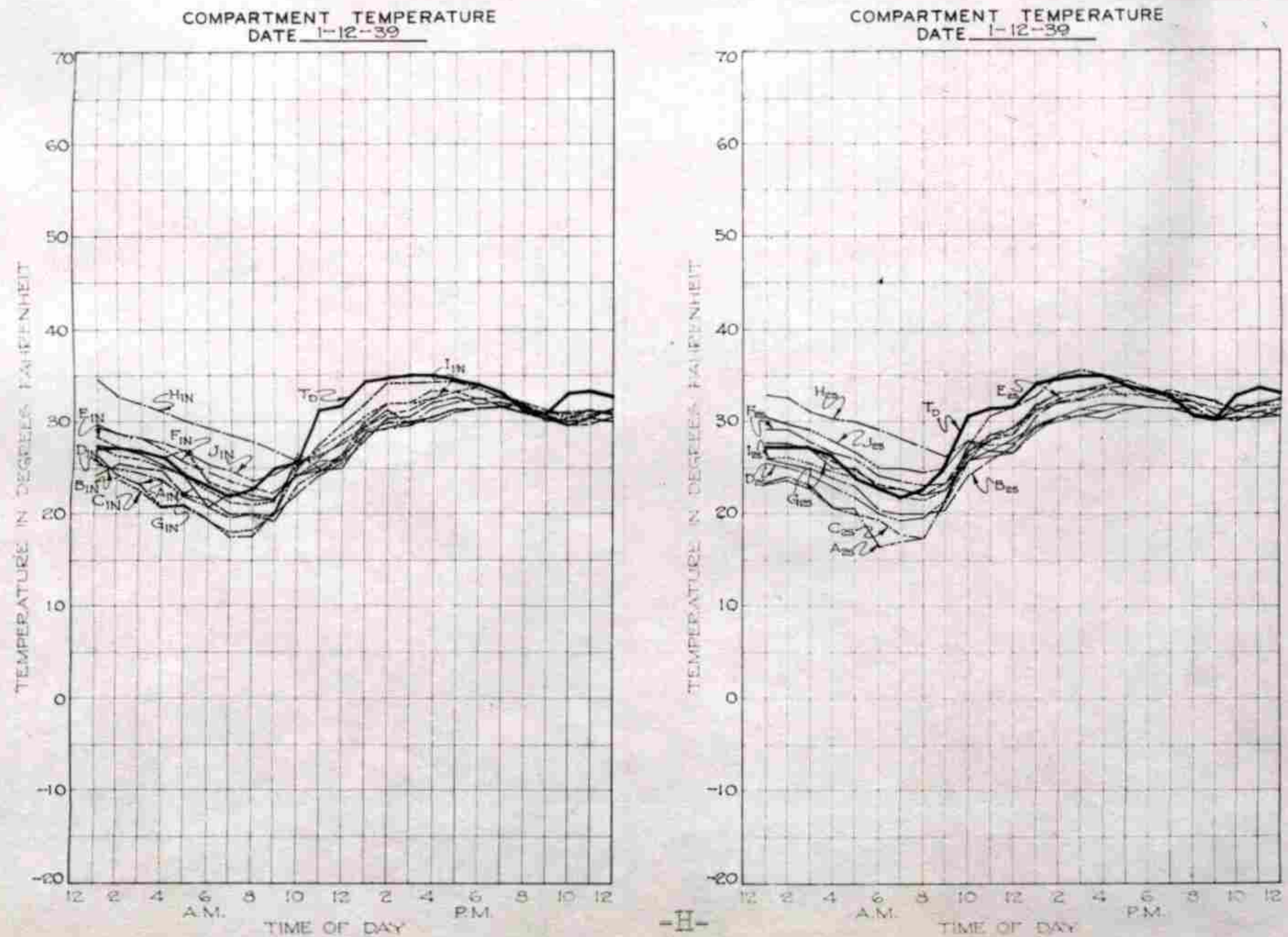

COMPARTMENT TEMPERATURE
DATE 8-13-38
COMPARTMENT TEMPERATURE
DATE 8-13-38
TEMPERATURE IN DEGREES FAHRENHEIT
TIME OF DAY
A.M.
P.M.
-E-
COMPARTMENT TEMPERATURE
DATE 9-24-38
COMPARTMENT TEMPERATURE
DATE 9-24-39
TEMPERATURE IN DEGREES FAHRENHEIT
TIME OF DAY
A.M.
P.M.
-F-

Fig. 17. (Cont.)



-G-



-H-

Fig. 17. (Cont.)

3. The diagrams in Fig. 18 show the difference between the outside air temperature, the compartment air temperature, and the outside surface temperature for each of the eight roof sections studied under summer weather conditions. For each roof section the upper set of curves show the north facing roof sections and the lower set of curves show the south facing roof sections, and the wind velocity plotted to the scale on the right-hand side of the diagram. Solar and sky radiation intensities are not plotted on these diagrams but may be obtained from Fig. 3 for Oct. 10, 1938.

From the compartment temperature diagrams other comparable criteria can be obtained to indicate in different ways the ability of the different roof sections to retard the flow of heat from solar radiation, namely:

1. The maximum compartment temperature for a 24-hour period when plotted for each roof section indicates in a relative way the amounts of heat which have entered through the various roof sections.
2. The minimum compartment temperature shows in a relative way the ability of the roof sections to lose their heat at night. While it is true that for this to be a valid indication each compartment should commence at darkness in the evening with the same temperature, actual observations as shown in the data indicate that the compartment

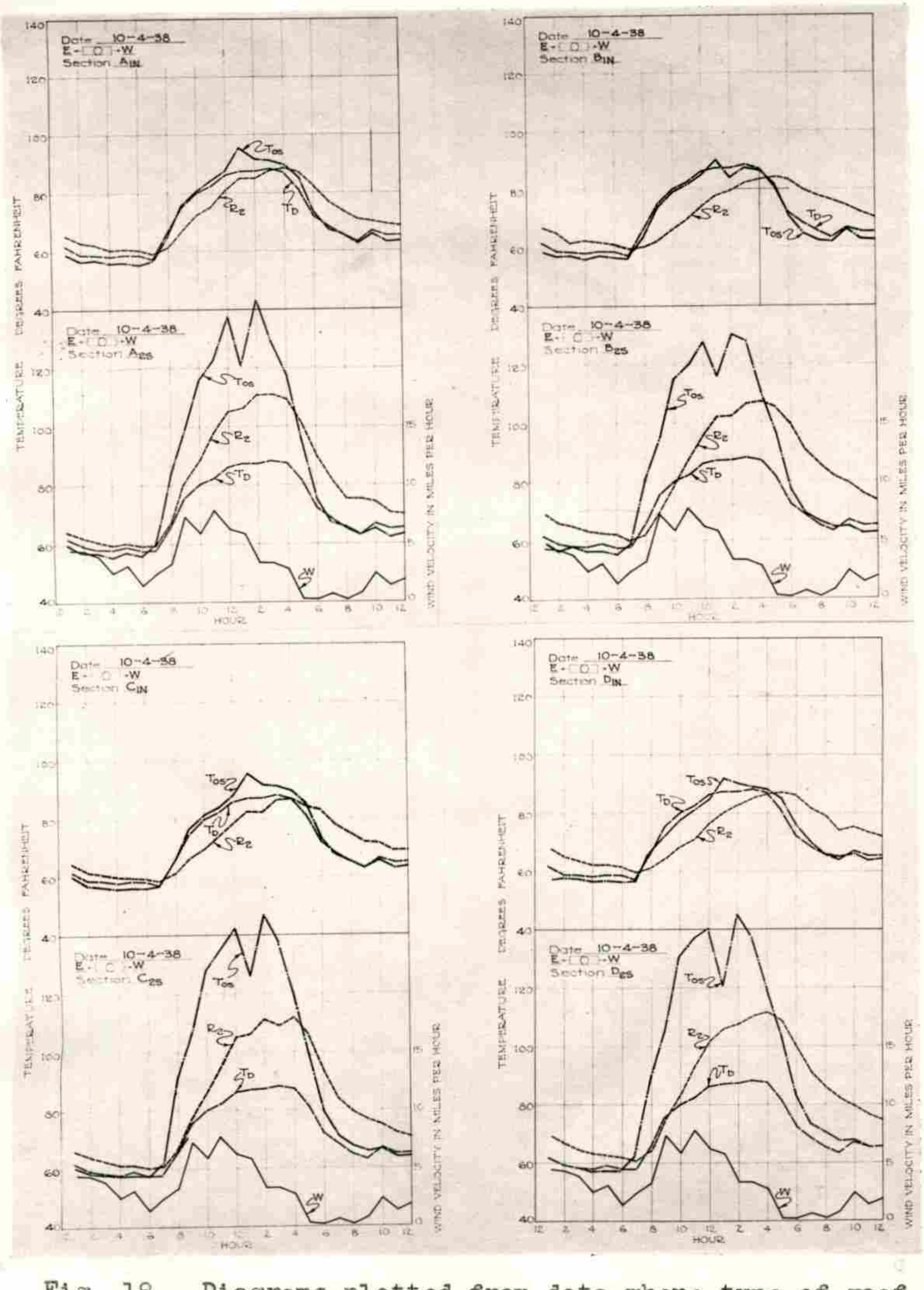
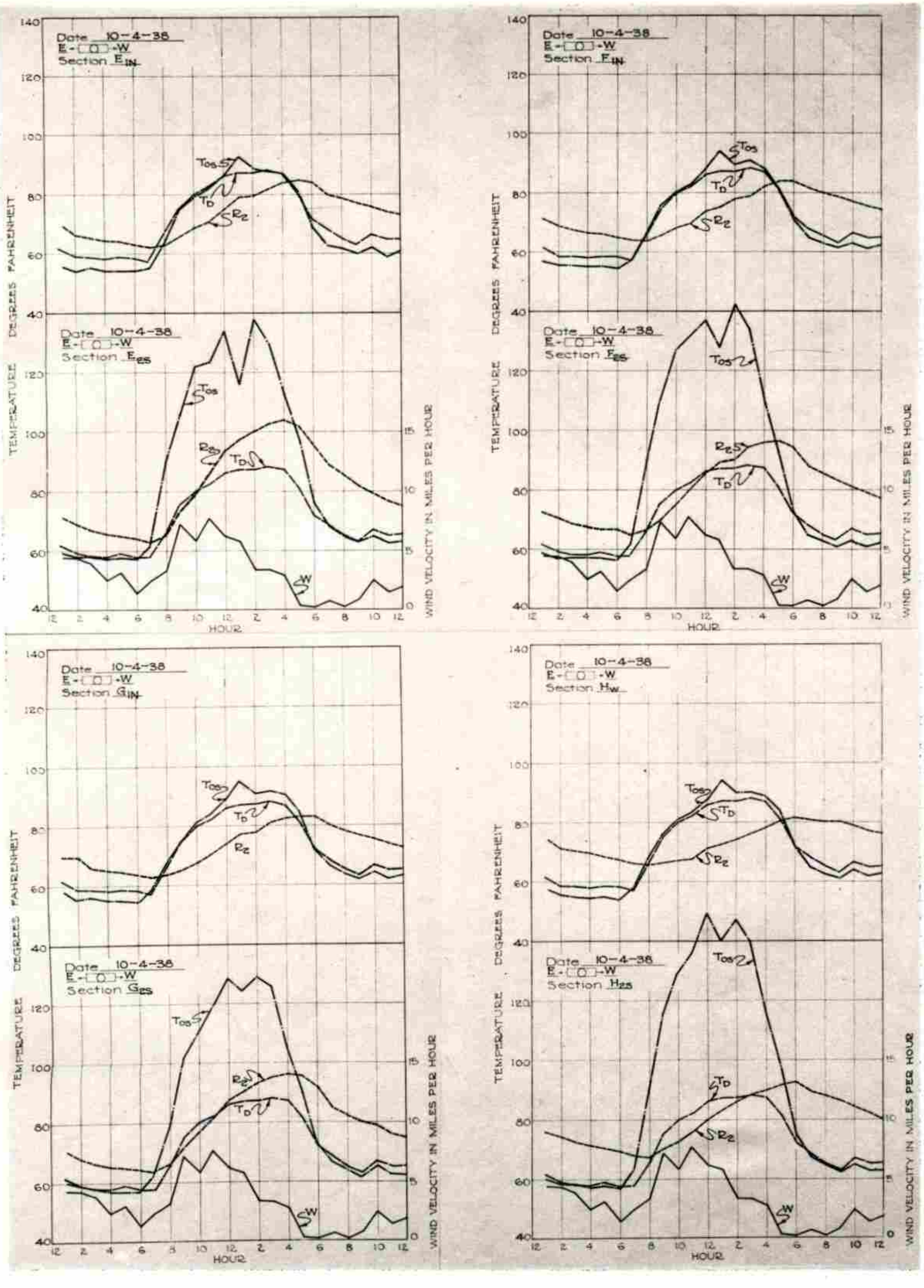


Fig. 18. Diagrams plotted from data where type of roof section is only factor different for each diagram



Date 10-4-38
E-[ ]-W
Section E_{IN}
Date 10-4-38
E-[ ]-W
Section E_{ES}
Date 10-4-38
E-[ ]-W
Section F_{IN}
Date 10-4-38
E-[ ]-W
Section F_{ES}
Date 10-4-38
E-[ ]-W
Section G_{IN}
Date 10-4-38
E-[ ]-W
Section G_{ES}
Date 10-4-38
E-[ ]-W
Section H_W
Date 10-4-38
E-[ ]-W
Section H_{ES}
T_{OS}
T_D
R_E
W
TEMPERATURE DEGREES FAHRENHEIT
WIND VELOCITY IN MILES PER HOUR
HOUR

Fig. 18. (Cont.)

with the highest temperature during the day attains the lowest temperature at night. Therefore, this reading plotted for a roof section indicates a practical aspect of the value of insulation in a roof section.

3. The maximum range of compartment temperatures, for each of the roof sections, shows a direct relative indication of the thermal insulation abilities for different roof sections exposed to identical environmental conditions.
4. Maximum rate of increase,
5. Maximum rate of decrease, and
6. Average rate of change, all show the ability of a roof section to maintain a time lag of temperature increase or decrease.
7. Percent greater range through outside air shows essentially the same comparison as does the maximum range of compartment temperatures but expresses it in another way.

The importance of the data items, 4, 5, and 6, above may be shown by an illustrative example. If a temperature difference of 100°F. were established across two walls, one exceedingly high in insulating properties and the other exceedingly low in insulating properties, the resulting temperature difference after a sufficient period of time would become zero for both walls, considering no other heat gains or losses. Therefore, the ability of a structure to retard or hold the heat flow until the outside air becomes cooler than the structure when heat can then flow back to the air, makes it desirable as an insulator to heat flow from solar radiation in the summer.

These comparisons for summer weather conditions are shown in Fig. 19 for the eight original roof sections.

Discussion of results

As previously stated the method of procedure in obtaining the temperature data was to secure a set of readings for each hour of the day. Consequently, each temperature was read only once each hour. On a day with slight air movement and with the sky partly clouded the outside surface temperature on a roof section was recorded every 30 seconds for a period of 10 minutes. During that time the surface temperature varied 10 degrees between maximum limits. Surface temperatures fluctuate rapidly under certain sky conditions. For these conditions of the sky an accurate determination of this fluctuation would demand readings not to exceed two minutes apart, making such a determination feasible only by the use of a recording pyrometer. The fluctuation of the compartment air temperature could be determined with sufficient accuracy by readings an hour apart, and since the data obtained in this study would not be materially improved unless the time interval of readings were reduced to at least two minutes, all

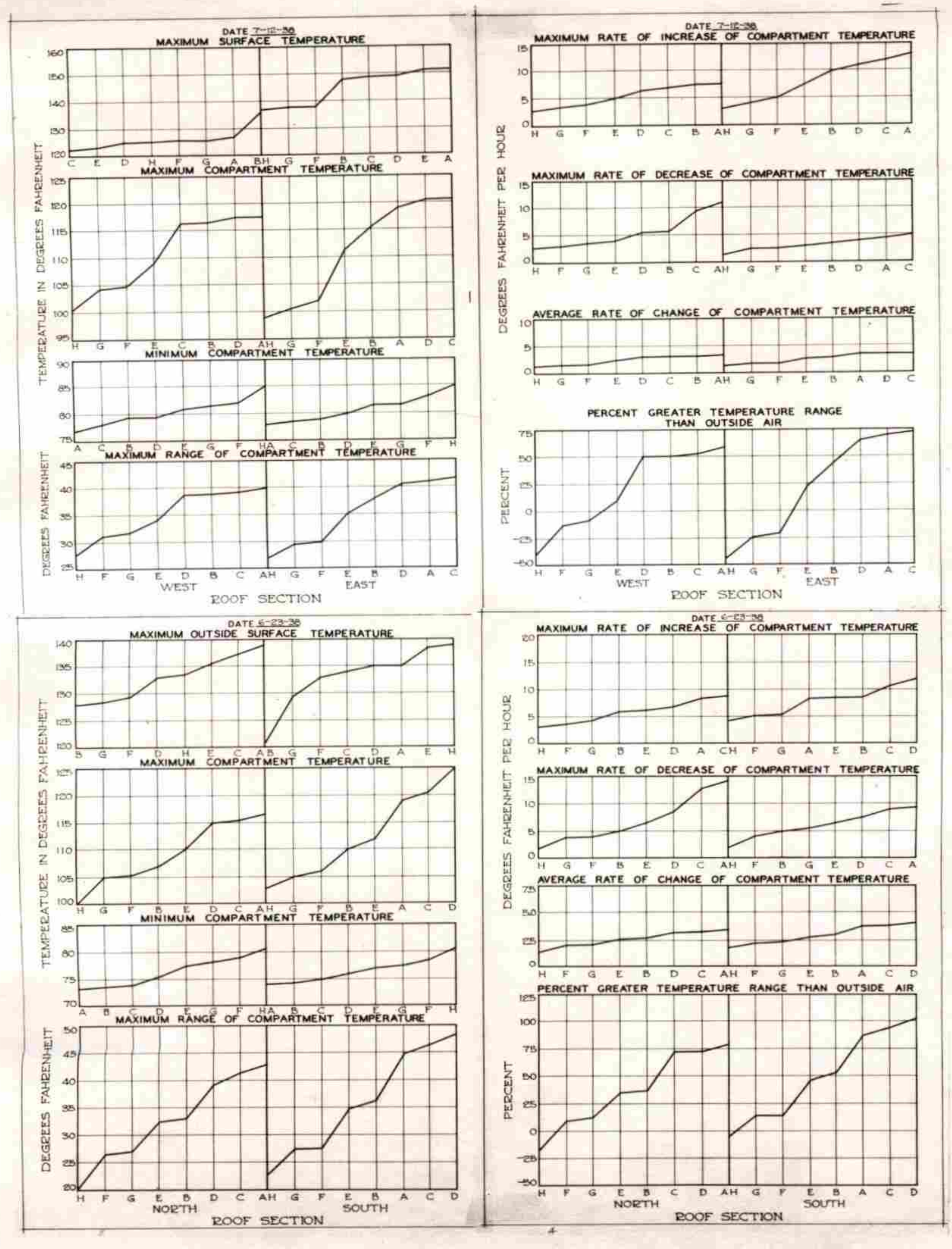


Fig. 19. Comparison of the eight roof sections
for summer weather conditions

temperature readings were taken just once an hour.

Much of the insulation ability of a structure is manifested by a time lag of its maximum temperature to that of the maximum air temperature and/or maximum radiant heat intensity. Therefore, to secure the proper information concerning the ability of the different roof sections to maintain this time lag, a set of readings for a cycle of weather conditions which make this feature possible would need to be for at least the period of the day. Consequently, the logical time to start and finish a unit of readings was at midnights 24 hours apart.

A study of the effect of orientation had indicated, for all practical considerations, that the only factor changed by a difference of orientation is the amount of impinging radiation that strikes the roof surface. The effect of wind direction, the only other factor being changed by orientation, would depend upon the constancy of the wind to come from a given direction. However, for winter in Iowa the prevailing wind is from the northwest and for summer it is from the southwest, which indicated that for a north and south or an east and west orientation the heat flow through the roof sections would be affected practically the same by this factor. In view of this a determination of the most favorable orientation for either winter or summer weather conditions would become a process of figuring the number of B.T.U./hr./sq. ft. of impinging radiation that would fall upon the roofs with the two orientations for sample days throughout the year.

It should be noted that for an ordinary gable roof building, which has the volume under the complete roof unseparated by an insulating partition, the total amount of radiation striking both sides of the roof should be combined to secure a valid comparison for the different orientations. The construction of the test-house and other important aspects of this study required a central partition dividing the volume covered by the various roof sections. This introduced an error for the direct comparison of the different orientations because greater temperatures would be reached under a roof section facing south, for instance, if there were a central insulating partition than would be reached under both facings if the volume of air at a considerably lower temperature under the north roof were not insulated from that under the south roof. The same holds true for an east and west facing. It is seen from the compartment temperature diagrams, Fig. 17, that for a certain type of roof section there is considerable difference between the two compartment temperatures for different times throughout the day, which complicates a comparison of the two orientations.

However, the study has been greatly enhanced since all four directions of the roof section facings were possible. This feature did provide a means of comparing the amounts of heat entering a roof section for each of the four directions of facing.

A comparison of the four facings shows that a south facing roof 45° to the horizontal allows the highest compartment temperatures, as shown in Fig. 17. This is a logical result in that the sun's rays throughout the year strike in a direction more nearly to the normal for this surface than they do for any of the 45° surfaces facing the other three directions. While, for average days the east and west facings receive almost equal amounts of impinging radiation, the fact that the air temperature is higher in the afternoon than in the forenoon produces higher compartment temperatures for the west facing. The north facing roof sections in midsummer receive considerable direct radiation, especially in early morning and late afternoon, but they do not receive it in quantities sufficient to produce compartment temperatures equal to those resulting from the other facings.

To study the effect of ventilation upon the compartment air temperatures a system of ventilator units were installed in the test-house in its original construction. These ventilator outtakes consisted of small hoods or caps which could be placed tightly over the outlets at the ridge of the roof or which could be lifted to provide ventilation. To provide an intake the manhole coverings for the different compartments were removed. A brief consideration of the flow of air by natural convection indicates that the air would tend to form convection currents parallel to the under surface of the roof sections, the characteristic desired, even though a straight line connecting the outtake with the intake does not pass along the under surface of the roof sections.

To thoroughly analyze the effects of ventilation the rate of air flow through the compartment and its rise in temperature between the intake and the outtake would have to be measured accurately. Obviously in a setup of this type those very difficult measurements would be quite impossible to secure accurately. Another important observation which should be made is that the reduction of the compartment temperature varies directly as the amount of ventilation, reaching a limit when conditions would be the equivalent of having equal free air circulation on both sides of the roof section. Therefore, the reduction of compartment air temperature is really a measure of the amount of ventilation. However, considering the relatively small cross-sectional area provided in the outtakes, the results obtained with the ventilators opened, Fig. 17-D, show quite clearly the capacity of air in carrying away heat.

The temperature data sheets, Fig. 15, are not only sample data sheets but also represent different sets of environmental conditions which could be shown in the form of a complete set of data. The sets of data represent the following conditions:

8-4-38. This set of data shows the approach of the complete test-house to the temperature of the outside air. The time of the readings occurred just after daybreak but before sunrise. The temperatures on the roof surfaces were slightly below that of the outside air temperature showing radiation to the sky.

1-19-39. This set of data shows the test-house with artificially heated compartments, see Table X, when exposed to a mild winter day with a clear sky. Since the temperature T_2 for roof sections, I_{2S} and J_{2S} is lower than either of the adjacent surface temperatures, no heat is passingacross the air space by conduction. This is an indication of the conditions which will be obtained for summer weather conditions for the two ventilated roof sections.

1-27-39. This set of data represents a set of conditions almost identical to those of 1-19-38 39?, described above, with the exception that the wind velocity is 17.4 mph faster and the outside temperature is 10° greater. The effect of the increased wind velocity on the temperatures throughout the south facing roof sections is quite marked.

2-3-39. Artificial heat was supplied in the quantities shown in Table X. This set shows the difference between the compartment temperatures for the north and south facing roof sections due to the different amounts of impinging radiation.

The temperature gradient diagrams shown in Fig. 16 have been chosen to show different typical environmental conditions of summer weather for the original eight roof sections and of winter weather conditions for all ten roof sections. Each roof section has been pictorially illustrated in the diagrams where each dot represents a thermocouple. The temperature gradient diagrams represents temperature data taken under the following conditions:

A. An average summer day; light breeze from southeast; partly cloudy.

B. Typical summer sky; partly cloudy; light breeze from southwest.

C. Clear sky; wind velocity, 7 mph from southeast.

D. Clear sky; wind velocity, 7 mph from south. T_{1s} or T_2 was off the inside surface of the corrugated sheet steel for this set of readings.

E. Near sunset; note surface temperatures on the north roof sections.

F. Clear sky; wind velocity, 2 mph from west; note surface temperatures on west roof sections.

G. Clear sky; light breeze from south.

H. Set of readings taken just after light shower. Sky was partly cloudy in the morning and early forenoon.

I. All compartment ventilators open, except compartment A; partly cloudy with light breeze from south.

J. Clear night with frost on roof; no artificial heat in compartments; note low surface temperatures. South roof sections were so nearly identical that they were omitted.

K. Clear sky; 8 mph wind from south; no artificial heat in compartments.

L. Artificially heated compartments, zero wind velocity; sky covered with clouds reducing reradiation to the sky.

To show how temperature gradient diagrams indicate heat flow, it is helpful to visualize them as projections of irregular surfaces, that are horizontal in the direction perpendicular to the gradients, on which rain is falling. The heat is flowing in the same direction that the water would flow after falling upon the surface. For steady heat flow conditions the rate of heat travel through each part of the section is the same. Therefore, in the analogy if the rate of water flow is going to be the same over each point on the irregular surface, a greater resistance to the water flow will have to be developed for the places where the gradient is steep than for the places where the gradient is nearly flat. This is the actual condition for heat flow in that the steeper the temperature gradient the greater is the resistance offered by the material through which the gradient is drawn to the flow of heat. While the above discussion applies accurately for only steady heat flow conditions, it still represents the fundamental concept of temperature gradients and may be used with correct indications in studying the temperature gradient diagrams, Fig. 16, between the points representing the outside surface and the inside air temperature. The principle cannot be applied to that portion of the gradients connecting the outside air to the outside surface, because when that part of the gradient has a slope opposite to the rest of the gradient, an altogether different portion of heat is flowing from the outside surface to the outside air than from the outside surface to the inside air.

One outstanding fact shown by the temperature gradient diagrams is the magnitude of the surface temperature. The ideal for surface temperatures of a roof section exposed to solar radiation would be to have them approach the outside air temperature. That this is far from the actual condition shows clearly that one of the major places for improvement lies in designing a roof surface or providing a practical means which will reduce this surface temperature to a minimum. Concerning the relative values of the surface temperatures, it should be noted that the surface characteristics for all the roof sections except type B are practically identical, making the difference in surface temperatures for constant environmental conditions an indication of the relative heat capacities of the roof sections. This explains why the surface temperature of roof section, type H, is higher than type A, when constant environmental conditions have been established. Another apparent observation is that for heat to flow both directions from a point in the roof structure demands a supply coming from somewhere by some method of transfer other than conduction. In the case of Fig. 16-A and B, for example, this heat is coming from solar and sky radiation. Also for Fig. 16-J, conduction heat is all flowing towards the surface of the roof where it leaves in the form of radiation to the sky.

The following relative characteristics of the different roof sections are shown in the temperature gradient diagrams:

Sections A and B. After heat is once established from impinging radiation on the surface, the only insulation properties of these two sections are due almost entirely to the inside surface film resistance. A 26 G. sheet of steel can be totally neglected with no serious error when figuring its resistance to heat flow by conduction. The effect of the reflective surfaces for galvanized sheet steel are included in the establishing of the outside surface temperature and in the resistance of the so-called "inside surface coefficient."

Section B. A structure of wood shingles over six-inch sheathing spaced eight inches on centers shows considerable insulation ability, due primarily to the thickness of shingles and the small air films between the layers of shingles. Surface temperatures of 150° have been recorded for this roof section.

Section D. Sisalkraft paper has little insulating value for transmitted heat. Its main feature is in the reduction of air infiltration, which in winter would be desirable. For summer weather conditions it would be classed as undesirable, because air exfiltration would then remove excess heat from inside the building.

Section E. The temperature gradient clearly shows that after heat has entered the outside surface the Celotex insulation board located directly underneath the sheet steel provides most of the resistance to heat flow through this section.

Section F. The 3 5/8 inch air space produces a temperature drop equal in many cases to twice the temperature drop of the Celotex insulation board fastened to the under side of the rafters. The surface characteristics of the two materials facing this air space are responsible for much of this resistance to heat flow.

Section G. In comparing the temperature gradient diagrams for roof sections, type F and G, it is clearly seen that the Celotex insulation board has a greater resistance to heat flow than does the sheet of flat galvanized sheet steel. However, for summer weather conditions the over-all insulation ability of type G appeared better than that of type F. As stated previously from 60 to 85 percent of all heat flow across an air space bounded by ordinary surfaces takes place by radiation. The air space in roof section, type G, is bounded by two relatively high reflecting surfaces which produce more resistance to heat flow than do ordinary surfaces, which are more nearly approached in type F.

Section H. It is quite apparent that the ability of roof section, type H, to retard heat flow is due to the high insulation qualities of cornstalk "loose-fill" insulation both to retard the flow of heat and to act as a heat storage permitting less of the heat entering the outside surface to reach the inside air. It might appear that the flat galvanized sheet fastened to the under side of the rafters in this section would act the same as the similar sheet in roof section, type G. This is improbable, because "loose-fill" cornstalk insulation is very dusty, and a light coat of dust over a highly reflective surface considerably reduces its reflective ability.

The compartment temperature diagrams, Fig. 17, have been chosen from the 24-hour cycle units of data to show the relative abilities of the different roof sections to retard the flow of heat from impinging radiation and/or an air temperature difference for the following days which are representative of different environmental and physical conditions:

A. 7-7-38. North and South orientation. This makes for an east and west facing. These curves show the effect of fluctuating amounts of solar radiation upon the compartment temperatures and the outside air temperature.

B. 7-8-38. North and South orientation. For both facings, roof section, type D, had the highest compartment temperature. Types A and C showed similar results in that their compartment temperature diagrams lie close together; also types F and G showed quite similar results. It will be noted that the iar temperature was lower than any of the east facing eight compartment temperatures. The west facing obtained greater compartment temperatures than those facing east, which is always true for a clear day, because the air temperature in the afternoon is greater than in the forenoon.

C. 7-12-38. North and South orientation. Examination of these curves show: (1) the lag of the minimum compartment temperatures to that of the minimum outside air temperature; (2) the superior abilities of roof sections, types F, G, and H; (3) the outside air temperature was throughout the day lower than the east facing compartment temperatures. The last characteristic indicated that throughout the day the outside air temperature tended to produce heat flow from the compartment to the air.

D. 8-2-38. North and South orientation with ventilators opened for all compartments except A. All ventilated compartment temperatures approached the outside air temperature with the better insulated roof sections lying close to the T_d curve, which would be expected. The position of the compartment temperature curves relative to the T_d curves shows clearly the effect of ventilation in its ability to carry away accumulated heat.

E. 8-13-38. East and West orientation. Compartments C and D have practically the same maximum air temperatures. Other compartments in this respect rank in the following order: A, B, E, G, F, H.

F. 9-24-38. East and West orientation. All the compartment air temperatures on the north side were lower than the outside air temperature in the forenoon, showing that there was a potential for heat to flow into the compartments from the outside air. Whether heat flowed directly from the air depended upon the magnitude of the surface temperature created by impinging radiation. The steep slope of the curves for the south facing compartments shows the effect of direct solar radiation on a south 45° exposure for that time of the year.

G. 10-14-38. North and South orientation. This set of curves shows the time of day when the east facing and west facing roof section compartments reach their maximum temperatures.

H. 1-12-39. These curves were included to show the effect of a cloudy day. The small variation of the compartment air temperatures is an indication of the constancy of all the factors affecting heat flow for this particular day.

The diagrams were plotted in Fig. 18 to show as the only varying factor the type of roof section. For each roof section the data from both facings are shown as labelled on the diagrams. With the exception of impinging radiation intensities, which can be obtained from Fig. 3 with a fair degree of accuracy, since this was a day with a clear sky, a measure of all the important factors affecting heat flow through a given roof section are shown on these diagrams. Many characteristic features will be noted, namely: (1) the rapid increase of the outside surface temperatures for the south facing roof sections between 7 and 10 A.M.; (2) the relative values during the day of the outside surface, the outside air, and the compartment air temperature for a given roof section; (3) the relative values of the different maximum outside surface and the maximum compartment air temperatures for the eight roof sections, and (4) the difference between the outside surface and the compartment air temperature for the north and south facings of the roof sections.

The results of an analytical study of the compartment temperature diagrams are shown in Fig. 19. These diagrams representing the different comparable critemia were obtained from the compartment temperature diagrams and are plotted for each type of roof section from left to right in order of their ability to possess what would be considered the most desirable characteristics for the criterion indicated by the title in each case.

The general ranking from the best, or one considered most desirable, to the poorest of the roof sections according to these criteria, as shown in Fig. 19, take the following order:

Maximum compartment temperature	H G F B E C A D
Maximum compartment temperature	A C B D E G F H
Range of compartment temperature	H G F E B D C A
Maximum rate of decrease of compartment temperature	H G F E B D C A
Maximum rate of increase of compartment temperature	H G F E B D C A
Average rate of change of compartment temperature	H G F E B D C A
Percent greater temperature range than outside air	H G F E B D C A

Conclusions

1. Roof section, type A, composed of 1 1/4-inch corrugated galvanized sheet steel roofing maintained slightly lower compartment air temperatures than did roof section, type C, composed of 3 V-crimp galvanized sheet steel roofing.
2. Roof section, type E, composed of Celotex insulation board placed immediately under 1 1/4-inch corrugated galvanized sheet steel roofing, offered more resistance to heat flow from impinging radiation than did roof section, type B, composed of wood shingles on 6-inch

sheathing spaced eight inches on centers.

3. Roof section, type D, composed of 1 1/4-inch corrugated sheet steel roofing fastened to solid sheathing with a sheet of Sisalkraft paper in between them, produced the highest compartment air temperatures of the eight roof sections studied under summer weather conditions.
4. The resistance to the flow of heat from impinging radiation for roof sections composed of 1 1/4-inch corrugated galvanized sheet steel and a one-inch Celotex insulation board can be materially changed by the placement of materials within the section, as shown in types E and F, where a 3 5/8-inch air space added more resistance to the section than when the two materials were adjacent.
5. A sheet of flat galvanized sheet steel offered, in many cases, more resistance to heat flow from impinging radiation in summer weather than did a one-inch Celotex insulation board, as shown in roof sections, types F and G.
6. Roof section, type H, showed the best ability to retard heat flow from solar radiation.

Measurement of Heat Flow Through Roof Sections

Design and construction of testing apparatus

The compartment temperature diagrams for 1-12-39, Fig. 17-H, show quite clearly the conditions for a typical winter day with solar radiation a minor factor. Since it is this type of day for which the design of the heating load for a building must be computed for winter weather conditions, whether it is heated by animals or by a mechanical heating system, the amount of heat lost by transmission through the roofs under these conditions should be obtained. Also as explained previously, to find indirectly the over-all resistance to heat flow of a structure it is necessary to know two factors, the potential for heat flow and the amount of heat flowing. Therefore, heating units were installed in the test-house roof section compartments: (1) to study the characteristics of the roof sections for typical winter conditions which exist for heated buildings and (2) to find the absolute resistance to heat flow for each of the ten roof sections.

To design the heating units, the amount of heat lost through the floor and roof of each compartment for the desired outside and inside air temperature difference was determined approximately through the use of the conductivity coefficients given in Table X. These were obtained from the American Society of Heating and Ventilating Engineers' Guide for 1937. From this analysis it was found that the approximate heat required to maintain a heating duty of 40°F. varied from 1.188 B.T.U. for roof section, type A, to 100 B.T.U./hr. for roof section, type H.

Two possible methods could be followed in supplying this heat to produce data easily interpretable:

1. An equal amount of a known quantity of heat could be supplied to each compartment. The resulting compartment temperatures would then show directly the approximate relative resistances of the roof sections. This indication would not be accurate because different compartment air temperatures would produce different amounts of heat losses in and out of the compartments.
2. The heat could be apportioned to maintain all the compartments at the same temperature. This would approach the ideal in studying the heat flow characteristics of the roof sections, because: (1) it would provide for equal mean temperatures of the roof section; (2) the relative amounts of heat inputs would indicate directly and accurately the relative resistances of the roof sections; (3) the heat losses to the outside air through the floor of the compartments would be the same, and (4) there would be no heat transfer between compartments. While

Table X. Constants for Figuring Over-all Heat Conductivity Coefficients for the Roof Sections*

Surface coefficient for 2.5 mph wind on galvanized sheet steel	= 1.4
Surface coefficient for 2.5 mph wind on ordinary surface	= 2.4
Surface coefficient for 15.0 mph wind on galvanized sheet steel	= 5.3
Surface coefficient for 15.0 mph wind on ordinary surface	= 6.0
Surface coefficient for still air on sheet steel	= 1.2 ?
Surface coefficient for still air on ordinary surfaces	= 1.65
C for shingles	= 1.28
C for paper and sheathing	= 0.71
C for Celotex	= 0.30
k for fir lumber	= 0.7
k for "loose-fill" cornstalk insulation	= 0.26
U for floor of compartments	= 0.053
U for all partition walls	= 0.062
Floor area for compartments A,B,C,D,E,	= 18.9 sq. ft.
" " " " F,G,H,I,J,	= 17.0 sq. ft.
Roof area for A,B,C,D,E,	= 26.7 sq. ft.
" " " F,G,H,I,J,	= 24.0 sq. ft.
Center wall for A,B,C,D,E,	= 18.6 sq. ft.
" " " F,G,H,I,J,	= 16.7 sq. ft.
Partition wall area (i.e. I-A)	= 9.2 sq. ft.
" " " (i.e. A-B)	= 10.1 sq. ft.
" " " (i.e. F-G)	= 8.16 sq.ft.

*The units for these coefficients are according to the definitions given on page 24. Their values were obtained from the A.S.H.V.E. Guide for 1937.

the design and construction of a device to maintain a constant temperature within an enclosed air space is entirely possible, it is obvious that ten or twenty such units would be rather impractical for this part of the study.

Since electrical energy is easily converted into measurable amounts of heat, electricity was used to supply the artificial heat to each compartment. The design required approximately 4kw. to provide the proper amount of heat for the control-room and all the compartments. With the door closed little ventilation of the control-room is possible. This made electric reflector heaters desirable. Since for future work electric motors might be essential, the maximum voltage drop under full load should not exceed 18 percent. With the transformer 900 feet from the test-house, the most feasible procedure was to tap the transformer at the voltage desired and transmit the current on a high line to the test-house. To provide 100-volt terminals and to maintain proper voltage regulation, the most feasible design to transmit the electricity resulted in a three-wire system with a 200-volt drop across the outside two wires and a 110-volt drop from either outside wire to the neutral or middle wire. The transmission line came from the top of the last pole near the test-house through 3/4-inch conduit pipe, which ran down the pole, under the ground and up through the central pier of concrete into the control-room, terminating at the fuse box and switch shown in Fig. 20.

For convenience the 110-volt terminals were used for the heating elements. To maintain the least possible voltage drop each side of the three-wire system should carry the same load, leaving no current in the neutral wire. To provide for this, the test-house was divided into four equal parts for heating, two parts being heated from each side of the three-wire system. A schematic wiring diagram of the test-house is shown in Fig. 22. A knife switch in the circuit, Fig. 20, for each compartment provided a means of reading the amperage input into each compartment. The voltages for the four circuits leaving the switch box could be obtained at the instrument panel or at a set of terminals for sections A, C, F, and H, as shown in Fig. 22.

To supply heat in the small quantities necessary for the various compartments, Mazda electric lamps and carbon filament lamps were used in sizes which would require only three receptacles for each compartment. These receptacles, located about eight inches above the floor and equally distributed over the horizontal area, were so placed that the heater units in no case were closer than a foot to the thermocouples R_2. Since more energy was required for the compartments I, A, B, C, and D than was required for E, F, G, H, and J, it was necessary to put the lights in the control-room on the latter side of the three-wire system.

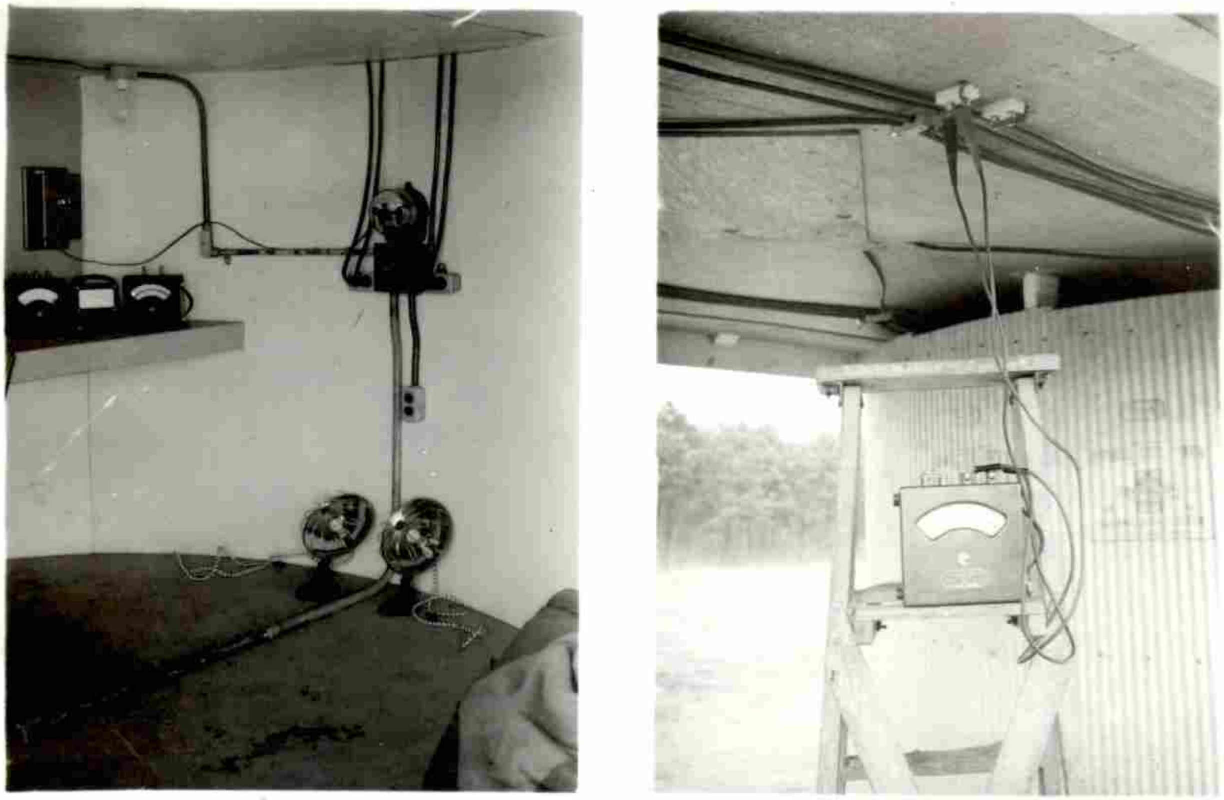


Fig. 20. Electrical installation in control room and method of reading current input into each compartment.

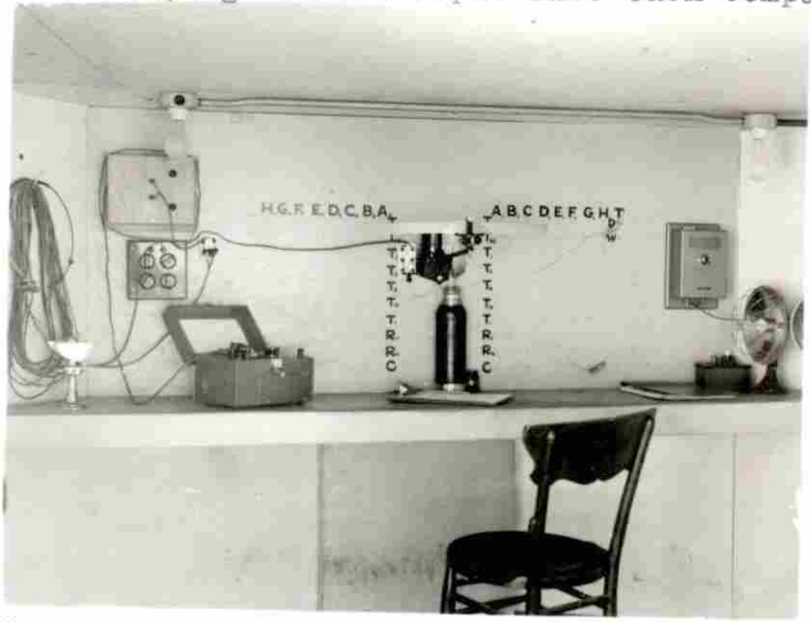
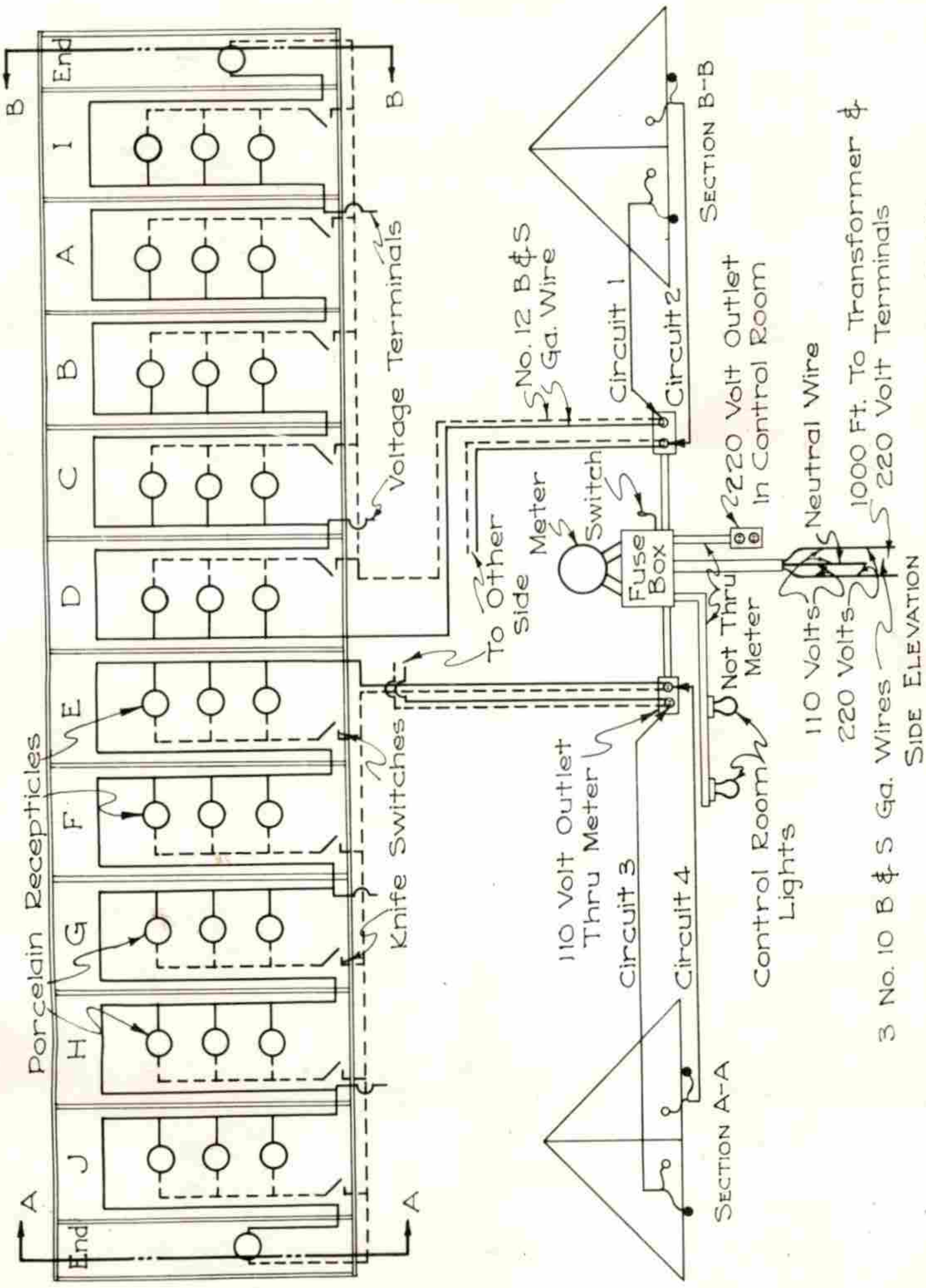


Fig. 21. Instrument panel in control-room.



ELECTRICAL WIRING CIRCUIT SCHEMATIC DIAGRAM

Fig. 22.

Putting two 110-volt, 600-watt heaters in series results in 300 watts input. Using this principle, the voltages for the four circuits were quite easily balanced. The A. C. ammeters, one with a two ampere range and one with a ten ampere range, and the A. C. voltmeter with ranges, 0-150 and 0-300 volts, used to measure the heat input into each compartment are shown in Fig. 20.

Heaters were placed in each of the four dummy compartments on the ends of the test-house. As a result the total energy registered by the watt-hour meter would be greater than the amount actually used in heating the 20 compartments, and since there was little voltage variation throughout the day, making the energy input constant, the watt-hour meter readings were not used in the computation of data.

Metod of procedure

After the heaters were turned on, at least five hours were required for steady heat flow conditions to be established throughout the test-house, other factors remaining the same. To obtain sets of readings when heat transfer by absorption or emission of radiant energy with the roof surface were a minimum, the condition existing at night with partly clouded skies was desirable with the time of reading being long enough after sunset for steady heat flow conditions to be established. The method previously described for observing and recording temperature data was followed with the exception that 24-hour cycle sets of data were not taken, because only one set of readings was required to determine the resistance to heat flow of all the roof sections for any one set of conditions.

The heat input into each compartment was determined by separate amperage and voltage readings. After the four circuits were balanced all loads were kept constant to maintain constant heat input into each compartment. The terminal voltage at the instrument panel remained practically constant throughout the day. Therefore, the accompanying amperage readings would also remain constant. As a result of this, a set of amperage readings were determined for a given terminal voltage and given set of loading conditions, these readings being used to compute the heat input by the following equation:

$$1 \text{ watt} = 3.413 \text{ B.T.U./hr.}$$

$$\text{or } EI = 3.413 \text{ B.T.U./hr.}$$

where E = the terminal voltage

I = the current for the compartment under consideration

The terminal voltage to compartments A, C, F, and H were found to be between 1/2 and 1 volt less than the respective circuit terminal voltages at the instrument panel. However, the four line voltages were used for their respective parts of the circuits. Table XI shows a set of voltage and amperage data.

Table XI. Set of Amperage and Voltage Data

Date 1-19-39								
Time	Voltage			Current in Amperes				
Circuit 1								
	E-1*	A_1°	C_1	I_1	A_1	B_1	C_1	D_1
8:30 P.M.	92.5	92.0	92.0	1.68	2.3	1.74	2.3	1.74
Circuit 2								
	E-2	A_2	C_2	I_2	A_2	B_2	C_2	D_2
8:30 P.M.	92.5	92.0	92.5	1.71	2.4	1.67	2.35	1.74
Circuit 3								
	E-3	F_2	H_2	E_2	F_2	G_2	H_2	J_2
8:30 P.M.	94.0	93.5	93.5	1.73	1.69	1.74	1.49	1.76
Circuit 4								
	E-4	F_1	H_1	E_1	F_1	G_1	H_1	J_1
8:30 P.M.	94.0	93.5	93.5	1.81	1.77	1.77	1.49	1.73

*E-1 Terminal voltage of circuit 1 at instrument panel
°Voltage of circuit 1 for the terminals at compartment A_1

Results

Table XII shows one set of experimentally determined values of the over-all conductivity coefficient, U, for each facing of the ten roof sections. It will be noted that

Table XII. Experimental Conductivity Coefficients for Roof Sections

Date:- 1-19-39 Wind velocity 2.7 mph		Time:- 11:58 P.M. Direction SE		Air Temp. 25.5° Sky; Dark; no stars	
Roof Section	Total Heat Input B.T.U./hr.	Amt. Gained or Lost B.T.U./hr.	Temp. Diff. T_1 - T_0 °F	Ave. Comp. Temp. T_1, R_1, R_2	Exp. U
A_1N	726	- 22.4	30.5	59.0	0.86
A_2S	757	- 24.8	34.0	59.6	0.80
B_1N	549	- 55.6	42.5	70.0	0.43
B_2S	527	- 52.4	45.0	71.0	0.39
C_1N	726	- 12.8	31.5	60.5	0.85
C_2S	741	- 47.0	45.5	68.5	0.57
D_1N	546	- 43.5	42.0	70.5	0.45
D_2S	550	- 46.4	46.5	72.5	0.40
E_1N	580	- 49.2	53.5	81.0	0.37
E_2S	556	- 59.0	56.5	82.5	0.33
F_1N	545	- 91.2	69.0	95.0	0.27
F_2S	542	- 63.6	63.0	89.0	0.31
G_1N	568	- 32.2	51.0	80.5	0.44
G_2S	558	- 44.0	51.5	80.0	0.41
H_1N	478	-105.0	75.0	101.0	0.21
H_2S	478	-110.0	74.0	102.0	0.21
I_1N	530	- 44.1	42.0	65.5	0.48
I_2S	540	- 38.4	40.5	64.0	0.51
J_1N	554	- 22.1	43.5	68.5	0.51
J_2S	564	- 26.6	46.0	73.0	0.48

neither the compartment air temperatures nor the heat input into each compartment were of the same value. To have provided either of these conditions would have necessitated either an exceedingly complicated setup to maintain constant temperatures or too great a difference in the mean roof section temperatures for equal heat inputs into each compartment. The heat gains or losses through the floor and partition walls were computed by using the values of the conductivity coefficients for these materials listed in Table X and were subtracted or added to the electrical heat inputs, the result being used to compute the values of U. The compartment temperatures used for these computations were the average values of T_1, R_1 and R_2. The air to air temperature difference was taken between T_o and T_1.

The results from different sets of data are listed in Table XIII. With the exception of the data for 2-2-39, when the moon was bright and the sky clear, each set of data represents environmental conditions existing when little heat loss or gain was due to impinging radiation or reradiation to the sky. The general information regarding the environmental conditions for each set of data is given in the table.

Table XIV offers a comparison of the experimentally determined values of U with the values computed for the roof sections from the constants given in Table X.

Table XIII. Tabulation of Experimental Values of U

Air Temp. ...	23.5°	23.5°	25.5°	37.0°	37.0°	29.0°	14.5°
Date........	1-19-39	1-19-39	1-19-39	1-21-39	1-28-39	1-31-39	2-2-39
Hour.........	10:00 P.M.	10:58 P.M.	11:58 P.M.	8:15 A.M.	8:30 A.M.	8:34 A.M.	10:20 P.M.
Wind Velocity	2.6 mph	3.2 mph	2.7 mph	7 mph	8.2 mph	15.4 mph	8.6 mph
Direction....	SE	SE	SE	SW	South	East	West
Sky..........	Dark Few Clouds	Dark No Stars	Dark No Stars	Cloudy	Densely Clouded	Densely Clouded	Clear Moon Bright
Roof Section: A_1	0.92	0.90	0.86	1.04	0.95	1.36	0.95
A_2	0.74	0.78	0.80	0.96	0.98	1.00	0.86
B_1	0.43	0.43	0.43	0.50	0.47	0.50	0.57
B_2	0.37	0.40	0.39	0.52	0.56	0.55	0.36
C_1	0.90	0.89	0.85	0.99	0.85	1.16	0.72
C_2	0.53	0.57	0.57	0.68	0.53	0.77	0.75
D_1	0.44	0.44	0.45	0.55	0.53	0.54	0.50
D_2	0.38	0.41	0.40	0.54	0.54	0.52	0.44
E_1	0.39	0.37	0.37	0.43	0.38	0.44	0.43
E_2	0.32	0.33	0.33	0.42	0.46	0.36	0.33
F_1	0.28	0.27	0.27	0.34	0.33	0.28	0.34
F_2	0.31	0.32	0.31	0.39	0.41	0.34	0.29
G_1	0.45	0.44	0.44	0.48	0.48	0.41	0.55
G_2	0.40	0.48	0.41	0.53	0.55	0.37	0.33
H_1	0.21	0.20	0.21	0.25	0.21	0.20	0.26
H_2	0.20	0.22	0.21	0.28	0.34	0.23	0.19
I_1	0.48	0.50	0.48	0.59	0.57	0.76	0.53
I_2	0.50	0.50	0.51	0.60	0.58	0.80	0.53
J_1	0.54	0.54	0.51	0.67	0.68	0.83	0.68
J_2	0.48	0.48	0.48	0.61	0.50	0.64	0.65

Table XIV. Comparison of Theoretically Computed Values with Experimentally Determined Values of U

Roof Section	Theoretically Computed Values of U: Wind Velocity 25 mph	Theoretically Computed Values of U: Wind Velocity 15.4 mph	Theoretically Computed Values of U: Percent Greater Value of U for 15.4 mph	Experimental Values of U: Wind Velocity 2.5 mph	Experimental Values of U: Wind Velocity 15 mph	Experimental Values of U: Percent Greater Value of U for 15 mph
A_1	0.64	0.97	51.5	0.89	1.36	52.8
A_2				0.77	1.00	29.8
B_1	0.37	0.40	8.1	0.43	0.50	16.3
B_2				0.39	0.55	41.0
C_1	0.64	0.97	51.5	0.88	1.16	31.8
C_2				0.57	0.77	35.0
D_1	0.37	0.44	18.9	0.44	0.54	22.7
D_2				0.40	0.52	30.2
E_1	0.215	0.24	11.6	0.38	0.44	15.8
E_2				0.33	0.36	9.1
F_1	0.164	0.18	9.7	0.27	0.28	3.7
F_2				0.32	0.34	6.2
G_1	0.31	0.37	19.3	0.44	0.41	- 7.3
G_2				0.43	0.37	-16.2
H_1	0.065	0.067	3.1	0.21	0.20	- 5.0
H_2				0.21	0.23	9.5
I_1	0.35	0.42	20.0	0.48	0.76	58.5
I_2				0.51	0.80	57.0
J_1	0.34	0.41	20.6	0.53	0.83	56.5
J_2				0.48	0.64	33.3

Discussion of results

The most obvious result appeared to be the noncorrelation of the over-all conductivity coefficients determined from the different sets of data. The most apparent explanation of this variation was due to the infiltration of air through the roof sections and at the ridge-roll. While all places where infiltration was apparent were caulked, on dark nights with lights in the compartments light could be seen coming through the seams and at different points at the ridge-roll of roof sections A and C. This shows a practical aspect of these sections, and in this sense these results are applicable for the actual conditions under which a roof exists on an ordinary building.

To study the difference between electric light bulb radiation and radiation of bodies at lower temperatures, two 600-watt heater coils were placed in series in compartments A_1 and C_1 and three 600-watt heater coils were placed in series in compartments F_1 and G_1 alternately with light bulbs of equivalent electrical energy consumption. With two or three 600-watt heater coils in series across a 110-volt potential the temperature of the heater wire is below that which produces any visible light. No measurable difference was found to exist between the resulting values of U due to the difference in the two sources of heat.

The set of temperature readings taken 2-2-39, shown in Table XIII, when the sky was clear with a bright moon in the south shows that the north facing outside surface temperatures were lower than the air temperature, while those on the south facing surfaces were above the air temperature. Under these conditions it is obvious that heat was leaving the surface of the north roof by radiation to the sky. The brightness of the moon apparently reduced the radiation to the sky from the south roof. As a result the values of U for the north facing roof sections, with the exception of roof section, type C, were higher than those for the south roof sections.

The readings for 1-28-39 gave higher values of U for the south facing roof sections, except for types C and J. The only apparent factor making for this difference was the direction of the wind, which was from the south. This would produce higher air velocities over the south roof sections.

A comparison of the theoretically computed over-all conductivity coefficients with those experimentally determined showed that the latter were considerable higher, especially in the case of roof section, type H. From the temperature gradients, Fig. 16, for 1-19-39 the values of C and k computed for the Celotex and cornstalk "loose-fill" insulation materials were 0.46 and 0.85, respectively, compared with the values of 0.30 and 0.26 obtained from Table X. Part of this difference for the "loose-fill" insulation probably resulted from an accumulation of moisture within the material. The principal factor appeared to be that only part of the heat was passing out through the roof sections by transmission. Exfiltration air through the closed ventilators in each compartment and through seams of the roofing most likely accounted for the remainder.

For different sets of data the value of C and k for these materials varied little from those given for 1-19-39.

The temperature gradient diagrams shown for 1-19-39 in Fig. 18 show clearly where the resistance lies to the flow of heat through each section. The surface film resistances for roof sections, type A and C, were greater than for the roof sections containing insulation. The resistance of the Celotex insulation board in roof sections, type E and F, is nearly the same, but the air space in type F adds considerably to its total resistance. The enclosed air space in roof section, type G, offers more resistance than does the ventilated air space in roof section, type J. The drop in the ventilation air temperature in roof section, type J, shows that heat is being carried away by the ventilating air. While undesirable in winter, this feature becomes desirable in summer. The effect of the highly reflective surfaces of the flat galvanized sheet steel of roof section, type J, is clearly shown by comparing its temperature gradient with that of roof section, type I.

Conclusions

1. Although special precautions were taken to prevent any transfer of filtration air, the results indicated that heat losses occurred from the compartments due to this type of heat transfer.
2. Roof section, type A, offered less resistance to heat flow due to an air temperature difference than roof section, type C.
3. Roof sections, types B and D, showed about equal resistances to heat flow due to an air temperature difference.
4. For the same conditions, roof section, type F, possessed more resistance, due to the Celotex insulation board than roof section, type G.
5. Ventilation within the roof section is not practical for winter conditions. Summer readings are necessary to determine its effect on heat flow due to solar radiation.
6. Roof section, type H, showed superior resistance to heat flow due to an air temperature difference.
7. Solar radiation for winter weather conditions materially affects the amount of heat flow through a structure, but due to its inconsistency it should be neglected when designing for maximum heat loads in winter.
8. The effect of a 12 mph. increase of wind velocity on the value of U for the well insulated roof sections, such as

type E, was small, while for those with little insulation, such as types A and C, the value of U was increased approximately 50 percent.

SUMMARY

This study was justified by the apparent need of a practical method to insulate roof sections covered with galvanized corrugated sheet steel for heat flow due to solar radiation and/or an air temperature difference.

The objectives of this study were: (1) to find the factors which affect the amount of heat entering a given roof section when exposed to solar and sky radiation, an air temperature difference, or both these conditions acting simultaneously; (2) to analyze these factors as to their nature and importance in affecting heat flow through a roof structure, and (3) to study and compare the relative abilities of different roof sections covered with galvanized sheet steel roofing with regard to their ability to retard heat flow from solar radiation and/or an air temperature difference.

An analysis of the environmental and physical factors affecting heat flow was made, and methods to measure each of these factors were presented.

A study was made concerning the relative abilities of eight different roof sections to retard heat flow due to solar radiation in summer and of ten different roof sections to retard heat flow due to an air temperature difference in winter.

CONCLUSIONS

1. It has been found convenient to divide all the factors affecting heat flow by transmission through a structure into, (1) environmental factors and (2) physical properties of the structure.
2. It is not feasible for man to control the environmental factors, which are constantly changing; while for a study of this type, once the physical properties of a roof section are established in its original constmction, they may be considered to remain fixed.
3. To study heat flow for a structure under actual weather conditions it is convenient to classify the environmental factors making for heat flow through a structure into those existing in, (1) summer weather and (2) winter weather .
4. Solar radiation is the critical factor making for heat flow through a structure when it is exposed to the sun in summer weather.
5. Air temperature difference across the structure is the critical factor making for heat flow in winter weather.
6. Wind velocity has no effect on heat flow through a structure unless there is a temperature difference.
7. If, as a result of further study, the total radiation

coming from various points in the sky can be determined for the various conditions of the sky, all the essential information will be obtained to determine accurately from one horizontal reading of the total (direct plus diffuse) radiation intensity to the total radiation striking a surface making any angle to the horizontal.

8. The ideal for increasing the resistance of a roof section to the flow of heat from solar radiation would consist in providing roof surface characteristics that would reduce surface temperatures to that of the outside air.
9. A highly polished white surface would approach this ideal.
10. When an air space bounded by ordinary surfaces exists within a structure, from 60 to 85 percent of all heat flow across the air space takes place by radiation.
11. Ventilation of an air space within a structure reduces only the convection heat transfer.
12. Ventilation of the air space within a structure is impractical for winter weather conditions. While studied for only winter weather conditions, ventilation of the 3 5/8-inch air space for roof sections, types I and J, showed results which would be highly desirable for summer weather conditions.
13. For heat flow due to solar radiation roof section, type A, was more efficient than type C, while for winter conditions with the critical factor affecting heat flow

being an air temperature difference, roof section, type C, showed more desirable characteristics than type A.

14. With solar radiation the critical factor affecting heat flow, roof sections, types B and E, showed equal abilities to retard heat flow, while with an air temperature difference, roof section, type G, showed more desirable characteristics than type A.

15. Under summer weather conditions with solar radiation as the critical factor affecting heat flow, roof section, type D, maintained the highest compartment air temperatures, making it the least desirable type of roof section of those studied.

16. Providing an air space within a roof section considerably increases the heat flow resistance of the sections, as shown in roof sections, types E and F, where the only difference was the 3 5/8-inch air space advantage possessed by type F.

17. Under summer weather conditions a sheet of flat galvanized sheet steel proved to be slightly more efficient in its resistance to heat flow than a one-inch Celotex insulation board, as was shown in roof sections, types F and G.

18. Roof section, type H, showed the most resistance to heat flow due to either solar radiation or an air temperature difference. The increased resistance of this

section was due primarily to the heat capacity and high insulating ability of "loose-fill" cornstalk insulation.

19. Ventilation of the compartments proved to be a highly efficient method to remove heat gains from solar radiation.

LITERATURE CITED

1. Abbot, C. G. & Aldrich, L. B. The pyranometer--an instrument for measuring sky radiation. Smithsonian Miscellaneous Collections. 66, No. 7. 1916.

2. _____ On the use of the pyranometer. Smithsonian Miscellaneous Collections. 66, No. 11. 1916.

3. Anon. Getting down to fundamentals--estimating sun's heat through walls and roofs. Heat. & Vent. 33, No. 4:37-40. 1936.

4. Barton, A. W. A textbook on heat. Longmans, Green & Co. p. 310. 1934.

5. Betts, M. C. A study of farm roofing. Agricultural Engineering. 11:403. 1930.

6. Deniston, A. J., Jr. The development and use of roofing nails. Agricultural Engineering. 17:9. 1933.

7. Fishenden, Margaret and Saunders, Owen A. The calculation of heat transmission. His Majesty's Stationery Office. London. 1932.

8. Goodman, William. Figuring solar heat gains of buildings. Heat., Piping & Air Cond. 10:391-4. 1938.

9. _____ 10:521-23. 1938.

10. Greig, A. R. Wall insulation. Saskatchewan University, College of Engineering. Bulletin No. 1. n. d.

11. Griffiths, Ezer. Report on heat insulators. Gt. Brit. Dept. of Scien. & Indus. Res. Food Investigation Board Sp. Rpt. No. 5. 1921.

12. Griffiths, Ezer & Davis, A.H. The transmission of heat by radiation and convection. Gt. Brit. Dept. of Scien. & Indus. Res. Food Investigation Board Sp. Rpt. No. 9. 1922.

13. Hand, I. F. Review of the U.S. Weather Bureau solar radiation investigations. Month. Weath. Rev. 66:415-41. 1937.

14. Houghten, F. C. & Gutberlet, Carl. Absorption of solar radiation in its relation to temperature, color, angle, and other characteristics of the absorbing surface. Trans. Amer. Soc. Heat. & Vent. Engrs. 36:137-152. 1930.

15. Kern, Joseph F., Jr. How to reduce heat loads due to sunlight on roofs. Heat. & Vent. 35, No. 7:38. 1938.

16. Kimball, H. H. & Hand, I. F. Daylight illumination on vertical and sloping surfaces. Month. Weath. Rev. 50:615-28. 1922.

17. Kimball, H. H. Records of total solar radiation intensity and their relation to daylight intensity. Mohth. Weath. Rev. 52:473-479. 1924.

18. Kimball, H. H. Variations in the total and luminous solar radiation with geographic position in United States. Month. Weath. Rev. 47:777. 1919.

19. Molenaar, Aldert & Perry, R. L. Flow of heat through roofs. Agricultural Engineering (In press). 1939.

20. Queer, E. R. Metallic heat insulation. Heat. & Vent. 31, No. 10:22-6. 1934.

21. Rowley, F. B. Insulating effect of a bright metallic surface. Trans. Amer. Soc. Heat. & Vent. Engrs. 40:413. 1934.

22. Rowley, F. B., Algren, A. B. & Blackshaw, J. L. Effects of air velocities on surface coefficients. Trans. Amer. Soc. Heat. Vent. Engrs. 36:123-36. 1930.

23. _____ Surface conductances as affected by air velocity, temperature and character of surface. Trans. Amer. Soc. Heat. & Vent. Engrs. 36:429-46. 1930.

24. Rowley, F. B. & Eckley, W. A. Surface coefficients as affected by direction of wind. Trans. Amer. Soc. Heat. & Vent. Engrs. 38:33-46. 1932.

25. Scoates, W. D. The effect of sheet steel roofing on interior temperatures. Unpublished Thesis. Library, Iowa State College, Ames, Iowa. 1938.

26. Severns, W. H. Heating, ventilating & air conditioning fundamentals. John Wiley and Sons. 1937.

27. Spriggs, R. E. Home manufactured "loose-fill" insulation. Unpublished Thesis. Library, Iowa State College, Ames, Iowa. 1936.

28. U. S. Bureau of Standards. Thermal insulation of buildings. U. S. Dept. of Com. Bur. of Stand. Cir. No. 376. 1929.

29. U. S. Weather Bureau. Pyrheliometers and pyrheliometric measurements. U. S. Weather Bureau. W. B. 1051. Cir. Q. 1931.

30. Wilkes, G. B. & Peterson, C. M.E. Radiation and convection from surfaces in various positions. Heat., Piping & Air Cond. 10:477-80. 1938.

31. Williams, D. G. Effect of insulation on surface temperature of the contents of galvanized corrugated sheathed buildings. Mech. Engr. 57:687-90. 1935.

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